EMERGENCE OF COLLECTIVE BEHAVIOUR

How Individual Regulation Matters in Elaborating Team Patterns in Football

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Universität Bern
Institut für Sportwissenschaft
Bremgartenstrasse145
3012 Bern

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PhD Thesis

Mathieu FEIGEAN

EMERGENCE OF COLLECTIVE BEHAVIOUR
How Individual Regulation Matters in Elaborating Team Patterns in Football

A thesis submitted
to the Faculty of Human Sciences
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Jury
Roland Seiler - **Supervisor**
Professor, University of Bern, Switzerland
Jérôme Bourbousson - Co-supervisor
Associate Professor, University of Nantes, France
Siegfried Nagel - Jury Chairman
Professor, University of Bern, Switzerland

At the University of Bern
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Ceci est une phase d'accumulation de capital symbolique infiniment forte, peu consciente, qui visait de façon presque avide à détenir des vecteurs de légitimation qui fassent que ma parole ne puisse être écrasée et que ma qualification sociale ne soit sujette à discussion. Ceci est le fruit de la reproduction sociale.

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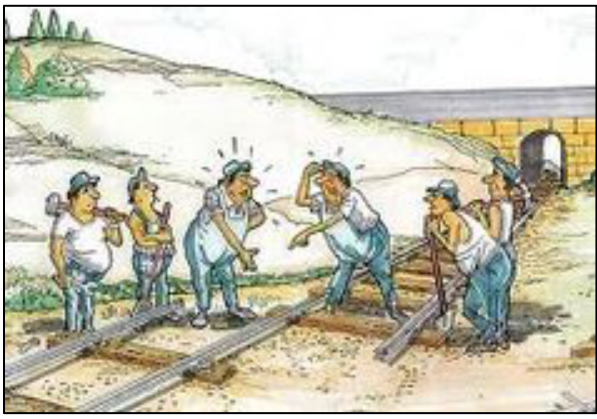
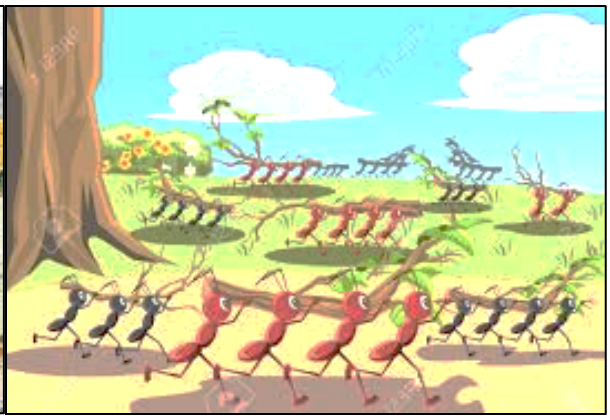
ELEVATOR PITCH

What is your PhD topic? It is a tricky task to answer the question that I frequently heard during the last *three years.* Even more difficult, every time that I answered this question, two others followed: *Is your PhD is useful for something or is it just for fun? But… why did you choose this topic?* ***I suggest here to answer, once and for all, these questions by starting with the last one.***

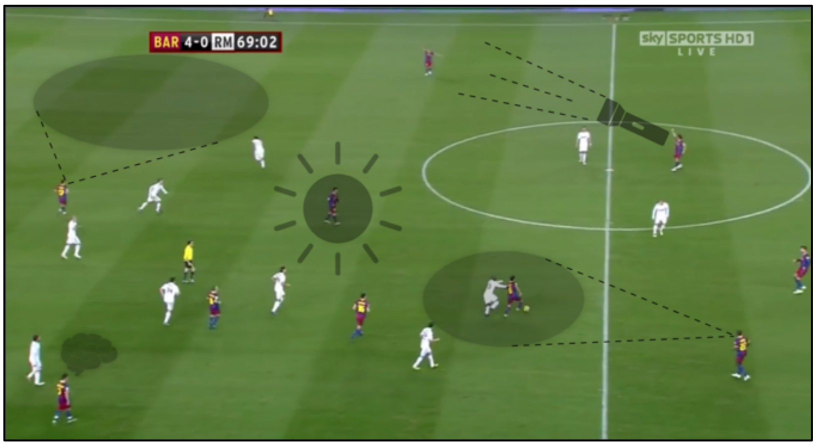
I personally think that one of the secrets of Ph.D. success is a deep, intrinsic motivation, which mainly characterises the pleasure that you have in going to work. And one good thing is that working on collective behaviour is, most of the time, a pleasure for several reasons. Collective behaviours are funny, fascinating and omnipresent. Collective behaviours are funny because they are unexpected. Some brilliant individuals can produce huge collective fails (e.g., Brazil lost against Germany, 7-1, in the 2014 World Cup) and sometimes teamwork demonstrates a success whereas no one individual is able himself to well perform (e.g., Greece, European Champions, 2004). Both are spectacular and not common, thus funny.





Collective behaviours are also fascinating. An ant could be stupid. It does not have much of a brain, no will, and no plan, but many ants together are smart. An ant colony can construct complex structures. Some colonies keep farms of fungi; others take care of cattle. They can wage war or defend themselves. How is this possible? How can a bunch of stupid things do smart things together? This phenomenon is call emergence, and it is one of the most fascinating and mysterious features of our universe. Schools of fish, termites, Mexican waves, crowds, and football teams illustrate the emergence phenomenon. It describes small things forming bigger things that have different properties than the sum of their parts. It is complexity arising from simplicity.

Collective behaviours are everywhere; schools of fish, termites, Mexican waves, crowds, and football teams are good examples. It is everywhere, yet water has vastly different properties than the molecules that make it up, like the concept of wetness. Wetness is an emerging property of water. Atoms form molecules, molecules form proteins, proteins make up cells, cells form organs, organs make up individuals, individuals form football teams.



To talk about my Ph.D., I decided to investigate the emergence of collective behaviour with football as a main object of study. Considering a team as a complex system, I currently think that emergence arises from the interactions of the players. The project attempted to understand how players regulate their behaviour to each other within the interaction to contribute to the collective behaviour. With the idea behind it that various individual regulations should imply various responses in the collective behaviour.

To talk about the usefulness of this project at the level of society, the question is complicated, but I can give you some examples more or less distant from what I did but still related to the topic. Firstly, this project could help coaches to improve their understanding of team behaviour and to develop new types of training. Secondly, there are probably some implications in robotics. By improving the knowledge of interaction processes, implications in the robot's coordination could work. There are actually many domains where we need a lot of robots working together: seabed cleaning, demining areas, space exploration. Finally, this project is more about fundamental research, and fundamental research is always useful.

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INTRODUCTION

Schools of fish, ant colonies, termites, the Mexican wave, human crowds, football teams – all reveal the beautiful side of what living beings can accomplish when they participate in collective behaviour. These phenomena suggest that collective behaviour is more than the sum of its components (Eccles & Tenenbaum, 2004). This project is born from a fascination with the beauty of these behaviours, at first sight difficult to explain, with a specific interest in collective behaviour in football.

Context. Collective behaviour has been intensively studied during the last two decades (Araújo & Bourbousson, 2016; Bourbousson, Sève, & McGarry, 2010b; Davids et al., 2014; Duarte, Araújo, Correia, & Davids, 2012; McGarry, 2009; Memmert, Lemmink, & Sampaio, 2017; Silva et al., 2014). The research on understanding team behaviour started with a focus on social psychology and the concepts of group dynamics, such as leadership, motivation (Cotterill & Fransen, 2016) and cohesion (Carron, Bray, & Eys, 2002). However, this area of research has missed one of the most important concepts, which is interpersonal coordination. Behind this, research topic on collective behaviour has shifted by considering that there is less to being a cohesive team than being an effective team (McEwan & Beauchamp, 2014). Researchers have sought to understand how the coordination of individual activities can exceed the products of their mere juxtaposition (Eccles & Tennebaum, 2004), thus signalling a form of collective intelligence. Team effectiveness has been assumed to arise from the base of teamwork as achieved by players (Eccles & Tenenbaum, 2004).

Interpersonal coordination that supports the team's effectiveness arises from the interaction among the activities of individuals. Past research was largely interested in analysing and understanding interactions between individuals. Considering collective behaviour to be the overall result of individual activities in interaction, the investigation of how players regulate their activity to contribute to the collective behaviour seems to be relevant. Individuals engaged in the same collective activity can adapt their activities to maintain their collective performance in a specific environment. In other words, individual activities to support interpersonal coordination are at the core of what emerges as collective activity.

Research that attempts to understand the emergence of collective behaviour is currently abundant in sports science (Araújo, Davids, Bennett, Button, & Chapman, 2004; Bourbousson, Sève, & McGarry, 2010a; Davids et al., 2014; Duarte, Araújo, Correia, & Davids, 2012; McGarry, 2009; Torrents et al., 2016). The emergence concept has been mostly explained in terms of dynamical systems theory. Dynamical systems theory describe the emergence of collective intelligence like in team sports as the appearance of new properties within group behaviour that cannot be reduced to the properties of individual behaviours. While understanding the dynamics of collective behaviour within dynamical systems is of particular interest in sports science, it also touches on many other areas, such as ethology and robotics. From a purely fundamental perspective, object of study flirts with concepts drawn from the theories of complex systems. Several studies in sport science have referred to this type of approach. For example, Bourbousson, Sève and McGarry (2010b) assume that it is possible to understand collective behaviours in sports as similar to natural behaviours such as *swarms* (e.g., schools of fish). In research on natural phenomena, studies have shown how simple local interactions can support complex collective forms that have surprising new properties.

Purpose. Considering the team as a complex system in which interactions are among the most fundamental elements, this project aims to investigate how players regulate their behaviour in relation to each other during the interaction process. This regulation includes the informational resources supporting the players' activity and the resulting behavioural adjustment. For example, a player could be focusing on a single team member – the informational resource – and attempting to maintain a stable distance from this team member – the resulting behavioural adjustment.

The rational for the present scientific project is elaborated based on the assumption that the process of regulation is at the heart of the dynamics of collective action. From this perspective, the dynamics of the collective activity produced by individuals are likely self-organised. This point of view has recently been formulated within the framework of the enactive approach to social coupling (Bourbousson, 2015; De Jaegher, Di Paolo, & Gallagher, 2010; Torrance & Froese, 2011) and also within the paradigm of dynamic systems of coordination (Haken, Kelso, & Bunz, 1985; Kelso, 1995; Oullier & Kelso, 2009). From this self-organisation of the dynamics of collective activity, produced by the interaction of the activities of the agents, emerges an autonomous phenomenological domain, a dynamic characteristic to the interpersonal encounter. This collective dynamic is not reducible to the individual perspectives of those who participate in the team behaviour, but it concretely exists through the influence it has on individual behaviours (De Jaegher & Di Paolo, 2007*).* This project is undertaken from an enactive approach.

The enactive approach has mainly provided theoretical arguments to the social human conception. In this approach, the focus is on the mutuality of interaction, which refers to the fact that social interactions concern simultaneously the agents who participate in the encounter and that the respective activities of these individuals are interdependent and affect each other. This characteristic is essential to the emergence of an autonomous collective activity. It is through the continuous effects that individuals have on one another that the process of interaction can self-organise and engender its own effects. The paradigm of dynamic systems applied to the study of interpersonal coordination has provided more empirical results on the self-organised nature of interpersonal coordination, without considering the mutuality of the effects the agents have on each other. The role of individual regulation in the elaboration of collective behaviour should be investigated. An embodied collective activity is, therefore, one of the central aspects of this project. Moreover, individual regulation is considered at a phenomenological level and a behavioural level.

Objectives. The aim of this project is to improve understanding of individual regulation itself and also to understand the role of this regulation in elaborating collective behaviour. First, we review the possible informational resources supporting the players' activities used in football. Second, by extrapolating the potential behavioural adjustments in response to these informational resources, we create a simulation model. We attempt to reflect individual adjustment modality changes and their correlates in collective behaviour. A complementary study focuses on the link between informational resources and adjustment but also on the ability to control regulation through interaction rules. This project is also a methodological challenge, given the need for both phenomenological data to characterise individual regulation modalities and simulation data to evaluate the behavioural correlates in collective behaviour.

Structure. In the first part of this work, which develops the scientific foundations, we discuss the state of the art in chapter 1, the scientific gaps in chapter 2, and the enactive approach epistemology in chapter 3. In the second part of the work, which presents the scientific contributions, we address the scientific rational in chapter 4, the general methodology in chapter 5, and empirical studies in chapter 6, closing with a general discussion in chapter 7. The final part of the work comprises a list of references, an overview of the author's scientific achievements, a list of figures and tables, and several appendices.

Scientific Foundations

Chapter 1: State of the art
Chapter 2: Scientific gaps
Chapter 3: Epistemology
Chapter 4: Rational
Chapter 5: Method
Chapter 6: Studies
Chapter 7: Discussion
References
Scientific achievements
List of figures & tables
Appendices
Statement of originality
Abstract

CHAPTER 1 - STATE OF THE ART

This chapter presents an overview of the studies conducted on collective behaviour in team sports. All of which build on the central idea that performance in team sports is more than the aggregate of team members' effectiveness (Eccles & Tenenbaum, 2004). Teamwork achievement has been explained according to different mechanisms, all aimed at improving the understanding of collective behaviour. From this foundation, we first argue for the need to investigate individual regulation within collective behaviour before we present assumptions about the various individual regulation modalities. The investigation of individual regulation involves diverse sources of data.

Chapter overview. This chapter first presents the current debate about the understanding of collective behaviour. With a primary focus on the interaction process, the second part of the chapter argues for the necessity of individual regulation in the elaboration of collective behaviours. Subsequently, we present our hypothesis about various types of regulation. The chapter ends by explaining the roles of the various data collected to study both regulation and collective behaviour at the same time. Together these elements structure our state of the art review, which should fill in all scientific gaps.

ELABORATION OF COLLECTIVE BEHAVIOUR

Describing what team members produce, how they behave on the field, and how they achieve team coordination in real time has been a main topic in team sport research in recent years (Araújo & Bourbousson, 2016). Three approaches to understanding collective behaviour can be distinguished: (1) investigating the properties of the individual activity that is part of a collective functioning, (2) investigating the collective as a unit and (3) studying the interferences between the individual and collective level.

Individual properties within collective behaviour

To account for collective activity, some studies have focused their analysis on the properties of individual activity (Converse, Cannon-Bowers, & Salas, 1993; Eccles & Tenenbaum, 2004; Reimer, Park, & Hinsz, 2006). Individual properties have been investigated in different studies according to two main focuses: (1) a description of individual behaviours included in the team and (2) a description of individual cognition within the team.

Description of individual behaviour. Traditionally, collective behaviour has been investigated by first investigating the properties of individual behaviour (Vilar, Araújo, Davids, & Button, 2012). Individual behaviour was described during all the game phases by providing accurate descriptions of the indicators of interest. For instance, important indicators of team performance in football include the team’s style of play. Team style has been described using two categories: *direct play* and *possession play* (Hughes & Franks, 2005). This collective behaviour performance was measured as the number of passes executed by all team members before scoring a goal. Hughes and Franks (2005) stated that the more a team passed the ball, the more the team style should be described as possession play. The results showed that the strike ratio of goals was better for direct play style than for possession play style. From a behavioural point of view, understanding collective activity through individual properties does not exclude the recognition that individuals must coordinate (Eccles & Tenenbaum, 2004), but the individual properties are considered to be primary. An example is the handling of a car accident: proper management of the accident will result from the performance of police, firefighters and emergency services, regardless of coordination needs (Kozlowski, Grand, Baard, & Pearce, 2015). In other words, collective performance is accomplished only if each individual is successful in the proper task.

Notational analysis approach. The description of individual properties has been developed in the theoretical framework of notational analysis. Notational analysis was established to objectively examine and describe behaviours of players during games to improve performance in team sports (Pollard, 2002). The notational approach allows description of the type of collective behaviour based on the individual properties but also allows identification of the individual profile within the collective behaviour. This approach does not afford a strong theoretical background, primarily due to a lack of key concepts. Additionally, this approach does not consider the interactions between team members and their dynamics as well as the ecological features of the game (Cooke, Gorman, Myers, & Duran, 2013).

Description of individual cognition. Collective behaviour has also been understood based on descriptions of individual cognitive processes. The principal assumption is to question why an expert team is more than simply a team of experts and is more than the sum of the individual performances. In contrast to notational analysis, coordination also has to be investigated. Coordination is defined, in this case, as a process of cognitive sharing between members (Blickensderfer, Reynolds, Salas, & Cannon-Bowers, 2010; Eccles & Tenenbaum, 2004, 2007). Cognition sharing between individuals induces complementary and similar mental models, allowing players to anticipate the needs of others and thus to coordinate. For this reason, coordination was characterised as explicit. Studies focused on the shared mental model through the study of phenomena such as shared knowledge and shared understanding (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). Blickensderfer et al. (2010) studied the correlation between shared knowledge and explicit coordination in doubles tennis. Researchers started by measuring the task experience and team familiarity of each member of a doubles pair with a questionnaire. From this, a score of shared knowledge was calculated. In parallel, experts in tennis were hired to evaluate the implicit coordination between the players in a pair. The study showed a significant correlation between shared knowledge and levels of implicit coordination. This study concluded that the arrangement of individual cognitive processes is a vector of collective performance. In this way, the work suggests that shared cognition in a team sport allow for better implicit coordination and, consequently, improved performance.

Social-cognitive approach. The first approach that investigated teamwork is the social-cognitive approach (Eccles & Tenenbaum, 2007) to interpersonal coordination. This approach focuses on these cognitive processes by inspecting the cognitive sharing between members of a team, and it postulates that members' sharing of similar mental models (i.e., shared mental models) are at the root of any form of collective intelligence. The social-cognitive approach (Eccles & Tenenbaum, 2004), assumes that teamwork is predicated on the notion of team cognition. A key aim has been to understand how shared knowledge can help team members coordinate efficiently in adapting to the dynamic demands of competitive performance environments. The assumption is that shared knowledge results from the team members having complementary goals, strategies, and relevant team routines that provide basic shared expectations about each other's actions. This allows them to coordinate and disregard completely new situational analyses of how the team should face unfolding game events. The social-cognitive approach, build on the human information processing approach, has adopted some similar methodology, such as the questionnaire and the verbal protocol (Blickensderfer et al., 2010).

Criticism of the social-cognitive approach. The social-cognitive approach has been challenged using two major arguments. First, because it gives primacy to the shared-knowledge hypothesis (Silva, Garganta, Araújo, Davids, & Aguiar, 2013), the social-cognitive approach has been accused of not accounting sufficiently for the situated nature of teamwork. The ecological feature of a situation is missed, while other approaches consider the ongoing situation as a main part of the collective behaviour. Second, the social-cognitive approach to teamwork neglects the key role of ongoing interactions in patterning collective behavioural states (Cooke et al., 2013). Thus, missing the embedded and embodied nature of human cognition (Froese & Di Paolo, 2011), this theory is not directly concerned with social interactions. Individual behaviours are regulated only by knowledge about the task and the team, and there is no concern about regulation in the ongoing situation.

Collective behaviour as units

Other research has considered collective behaviour as a unit, with team efficiency being described as emerging from the coordinated behaviours of the members. This phenomenon of emergence leads these researchers' to consider the collective as an autonomous unit, investigable in itself, thus team sports are described as *superorganism*s (Duarte, Araújo, Correia, et al., 2012). For this reason, most of these researchers' have tried to capture stable behavioural patterns that underlie collective behaviour. Their examination focuses on the dynamics of space-time features in sport, which seem to be a vector of performance.

In these conditions, analysing the spatiotemporal structure and dynamics has been relevant for defining the collective behavioural patterns associated with performance. As an example, researchers have shown that collective behaviour performance improves when the variability of the centre of gravity and the variability of the stretch index of the team conform to a specific pattern (McGarry, Anderson, Wallace, Hughes, & Franks, 2002).

In this framework, analysis of behavioural patterns to inform dynamic systems contains several objects of study (Travassos, Araújo, Correia, & Esteves, 2010; Travassos, Davids, Araújo, & Esteves, 2013): (1) the player–player dyad as an analysis unit, and (2) the team–team relationship in a game situation. Under the first category, McGarry et al. (2002) dealt with dyadic coordination in racket sports. Researchers (McGarry, Anderson, Wallace, Hughes, & Franks, 2002; McGarry, Khan, & Franks, 1999) showed that the behaviour of the squash dyad showed non-linear properties of dynamic systems. Other researchers extended these results to tennis (Palut & Zanone, 2005). The results pointed out that several attractors showed stability properties in the spatiotemporal interactions between the players. Based on angular measurements referring to the centre of the field, researchers were able to identify, on the one hand, recurring behaviours which define the attractors and, on the other hand, significant dynamic transitions of interaction between players. Moreover, Bourbousson et al. (2010a) studied one by one the dyadic coordinations within a collective. The case study allowed for updated mapping of the dyadic interaction networks (Bourbousson, Sève, & McGarry, 2010a) and contributed to the knowledge of the underlying structures of the spatiotemporal interaction, signalling an interest in the theory of dynamic systems for analysing sports collectives.

In addition, researchers investigated the team–team relationship at the level of the match (Bourbousson, Sève, & McGarry, 2010b). Bourbousson et al. (2010b) have identified patterns of coordination between two teams. This study offered the possibility of understanding the collective activity that resides in the phase that precedes a basketball shot. Macroscopic analysis was relevant in a dynamic approach, with each team considered an autonomous system. These studies generated a collection of video data and a statistical treatment of observed behavioural variables. Their results showed that the relative-phase relation for the stretch index was in in-phase attraction in the longitudinal direction and exhibited no attraction to any values in the lateral direction. The difference between the two stretch indexes is explained as phase transitions between two stable patterns. This suggested reciprocity between teams in their degree of expansion and contraction when possession of the ball was won and lost.

Research in football also highlighted the need to investigate collective behaviour as a unit (Clemente, Couceiro, Fernando, Martins, & Rui Mendes, 2013; Clemente, Couceiro, Martins, Mendes, & Figueiredo, 2013; Duarte, Araújo, Davids, et al., 2012; Frencken, Lemmink, Delleman, & Visscher, 2011; Frencken, Poel, Visscher, & Lemmink, 2012; Memmert et al., 2017; Memmert & Raabe, 2018; Moura, Santana, Vieira, Santiago, & Cunha, 2015; Perl & Memmert, 2017). Spatiotemporal analysis in particular has been a main focus (Gudmundsson & Horton, 2016; Gudmundsson & Wolle, 2014)

Ecological approach. Results that explain teamwork using an ecological dynamics framework (Araújo, Davids, & Hristovski, 2006) are based on the idea that team behaviour can be investigated in terms of its own dynamics without investigating individuals' internal cognitive processes at the micro level. Teamwork as the interpersonal interaction process leading to team behaviour is considered to occur between biological rhythmic units that are connected informationally (Araújo & Davids, 2016). Such informational connections between team members are assumed to be driven by affordances defined as opportunities for action (Gibson, 1979). The concept of affordances assumes that the environment is directly perceived in terms of what actions an agent can take and is not dependent on the players' expectations or mental representations (Richardson, Shockley, Fajen, Riley, & Turvey, 2008). On a social level, shared affordances are assumed to govern the arrangement of many individual behaviours (Silva et al., 2013). Thus, teamwork depends on the team's collective perceptual attunement to a landscape of environmental constraints. Therefore, based on their situational perceptual readiness, players become capable of refining their behaviours to functionally adapt to what they perceive as team coordination opportunities. From this view, teamwork-related concepts (e.g., division of labour; Duarte, Araújo, Correia, & Davids, 2012) have been investigated based on the assumption that interpersonal patterns that are observable at the behavioural level are sufficient to reveal the key environmental constraints that underlie team coordination. While acknowledging the main role of situated interaction between team members in helping collective behaviour emerges, the ecological dynamics approach has been analysed as reflecting an ontological *realism* (Varela, Thompson, & Rosch, 1991) in that it considers affordances as existing in the real material and physical setting and views them as something that can be revealed through behavioural methods. In contrast with this view, some authors have considered humans as primarily coupled to a meaningful world rather than to a physical one (Varela et al., 1991). In this sense, researchers assume a framework of analysis of the collective functioning starting from the postulate that teams are superorganisms (Duarte, Araújo, Correia, et al., 2012). These superorganisms are dynamical systems characterized by a set of interacting elements that present an emerging collective behaviour determined by self-organising properties that result from the large number of information exchanges within the supergorganism (Gibson, 2014).

Dynamical system theory. The ecological approach has largely adopted dynamical system theory to investigate collective behaviour. A system is defined by many components which interact with each other and with their environments. This system becomes dynamical when it changes over time. Most of the system change over the time, this change is called *bifurcation.* This bifurcation allows a system to switch from a stable behaviour to another one. The stable state is called an *attractor*. By attempting to describe the dynamical system as a whole, complexity has been demonstrated by deducing the macroscopic behaviour. The macroscopic behaviour has been explained thanks to the *collective variables*. Collective variables capture the order (e.g., synchrony) present within the system. These collective variables are usually called *order parameters*. Order parameters describe the patterns of the collective system. From example, they describe the phase or antiphase of the bimanual task coordination. While the macroscopic level is defined with the order parameter, the microscopic level is based on a *control parameter*, which is defined as a variable capable of modifying the essentials of team behaviour (i.e., the order parameters) when the variable value evolves beyond a critical value (Davids et al., 2014).

In line with dynamical systems principles, in team sport, metrics have been considered to characterise the collective behaviour, thus describing the *order parameters*. Previous research based on the dynamical systems approach to team sport has focused primarily on how some metrics, such as surface area, can serve as parsimonious macroscopic descriptors (Ric et al., 2016) of what happens in the social system (Duarte, Araújo, Davids, et al., 2012; Passos, Araújo, Davids, Gouveia, Serpa, et al., 2009; A. Ric et al., 2017). The local constraints observable at a more microscopic level of description were designated *control parameters*. Finally, the dynamical system describes a self-organisation by considering that process by which the pattern at the global level of a system emerges from interactions among microscopic components of the system. Considering this definition and the description of a dynamical system suggests that this theory can be applied to the dynamics of group cognition (Palermos, 2016).

Ecological dynamics framework. Based on dynamical systems theory and the concepts of ecological psychology, the *ecological dynamics* framework arose as a strong theoretical approach to reveal the rule that affects team behaviour (Araújo, Silva, & Davids, 2015; Travassos et al., 2010; Vilar et al., 2012). The ecological dynamics perspective allows a better understanding of coordination in team sport. Collective behaviours are described as performer operating in integrated systems composed of many interactors (attackers and defenders) that can self-organise to satisfy specific performance in environmental constraints (Keith Davids, Button, Araújo, Renshaw, & Hristovski, 2006; Passos, Araújo, & Davids, 2013; Silva et al., 2014). Within this framework, sports teams have been described as social neurobiological systems in which players are able to adjust their behaviours to modify the ecological constraints of performance environments to succeed (Button et al., 2013; Passos, Araújo, Davids, Gouveia, Serpa, et al., 2009).

Criticism of the ecological dynamics approach. First, this approach to collective behaviour involves the identification of non-accidental behavioural correlations among several interacting individuals. These non-accidental behavioural correlations can be captured by various tools, as developed by dynamical systems theory (Guastello, 2017), or by spatiotemporal configurations (Gudmundsson & Horton, 2016). Nevertheless, an identifiable non-accidental behavioural correlation is not sufficient to consider that collective behaviour has emerged from the interaction between individual agents.

Second, ecological dynamics theory assumes that collective behaviour can be investigated in terms of its own dynamics, disregarding how interactions are linked to individuals' internal cognitive processes. For instance, studies conducted within this approach developed tools capable of capturing team properties on their own, notably by elaborating team metrics such as the centroid position, the stretch index or the surface area of the team. However, this research neglected to provide a clear description of how the microscopic level of the system is implicated in the self-organised behaviour (Bourbousson & Fortes-Bourbousson, 2016). In other words, previous researchers, following ecological dynamics theory, adopted a prism that overlooked the way individual interactors in the system manage their own space-time interactions. When one considers humans to be uncertain interactors who are not determined solely by external factors, are able to inhabit their own very distinct worlds (i.e., they have subjective perception and experience their own phenomenological world in which they pursue their own intentions) and are free to change their interaction modalities while disregarding observable environmental reasons (De Jaegher & Di Paolo, 2007), a research gap remains in the ecological dynamics approach when one seeks to described how individual interactor perspectives influence team behaviour.

Third, the ecological dynamics approach to teamwork rejects the description of what team members live in real time when coordinating with others, thus missing the meaningful nature of any affordance and the underlying sense-making activity that helps affordances emerge (Fultot, Nie, & Carello, 2016). In other words, if individual behaviour is embedded in the environment, it is achieved within a field of affordances that should be investigated by considering the ongoing actors' *own world* – that is, how each member singularly builds and experiences his or her world (Rietveld, Denys, & Van Westen, 2016).

Finally, it is also necessary that the actors actively regulate the dynamics of their interpersonal coordination at the level of their local couplings. Specially, a flow of information exists between the agents, and this flow is actively and dynamically regulated by the actors. The experience of the agent should increase the understanding of team behaviour. In the Chapter 3, we present an approach that answers all the preceding criticisms and also fill the scientific gaps presented in Chapter 2.

Interferences between individual and collective properties

The understanding of collective behaviour has been improved by the ecological dynamics approach. However, this area of research has neglected the fact that the individual level is involved in the elaboration of the self-organised system. To bridge this gap, some studies have attempted to consider the mutual influence of the individual and the collective behaviour in the construction of collective performance. The actions of individuals are both constrained by the collective behaviour and contribute to the elaboration of this same collective behaviour.

Individuals are integrated into the system and entirely separate in the system. Based on this idea, several levels of analysis have been conceived to understand the overall activities and the associated links in a complex system.

Levels of analysis. The level of the individual has been called the microscopic level, the dyadic relation between individuals or all the subsystems has been called the meso-level, and the level of overall team understanding has been called the macroscopic level (Araújo, Passos, et al., 2015; Bourbousson, R'Kiouak, & Eccles, 2015). At the micro-level of analysis, the main focus is on the cognitive process that players use (Bourbousson et al., 2015) or on the individual spatiotemporal behaviour and the attitudes (Bourbousson, Deschamps, & Travassos, 2014). At the meso-level of organisation, the focus is on the dyadic relationship as the maintaining of distances between two players (Passos et al., 2011). At a macro-level of organisation, the focus is on the overall team. However, the main interest is to understand the interferences between the micro- and macro-level of analysis.

Micro–macro links. The governing principle for this area of research has been to improve the understanding of how team behaviour emerges from the interaction of individuals. By considering interferences between micro- and macro-levels of analysis, researchers have attempted to understand the collective behaviours at different levels of system analysis in team sports (Araújo, Passos, et al., 2015; Bourbousson et al., 2014; Silva et al., 2014). Thus, understanding micro-macro interference is a central issue in team sport science because it is directly related to interpersonal coordination of behaviour in the complex system. The key concept of transition or bifurcation justifies the interest in interference. As discussed above, transitions are those points when a global behaviour shifts from one pattern to another. For example, an experiment on bimanual finger movements reported that beyond a critical frequency the coordination pattern between two fingers changed (Haken et al., 1985). When the frequency of the finger movement was low, the coordination was out of phase (i.e., antisymmetric), whereas when the frequency was high, the pattern was replaced by an in-phase (i.e., symmetric) coordination (Haken et al., 1985). This suggests that the macro-level analysis described two patterns which are separated by a transition (Araújo, Passos, et al., 2015). Moreover, this transition was tied to the fingers' frequency, which is examined at the microscopic level of analysis. To conclude, the transition that gave two different patterns was made by changes in the level of finger movement frequency (i.e., microscopic level). However, the identification of patterns is not as easy when the number of interactors increases, and these difficulties in understanding tactical behaviour in team sport are quite clear. Some studies have investigated the micro–macro-level interferences in team sport (Bourbousson et al., 2014).

Spatiotemporal interference. Bourbousson et al. (2014) examined the multi-level nature of constraints in a basketball game. The researchers focused on the individual level by investigating the dyadic relation between a drive from one offender with the nearest defender and the relation between a drive from one offender and the team behaviour. They considered that the description of these levels was the most explanatory for understanding the decision making of a player (i.e., driver decision). The results indicated that the beginning of a drive was not preceded by a disturbance at the dyadic level (i.e., there was no significant difference in the variability of the relative phase), so fluctuations were point in the inter-team level. The drive was supported by changes in the centres of gravity and the stretch index. This result points to the inter-individual relations that seem to be at the heart of the action and are characterized by spatiotemporal constraints at the level of the team. This suggests the relevance of considering several levels of analysis and the interferences between them. Finally, from a methodological point of view, this study was interested only in behavioural data (Bourbousson et al., 2014). This perspective introduced here indicates to what extent events occurring at the level of global coordination can constrain or govern the local individual activity of the players.

Intersubjective interference. Another study was also interested in multi-level analysis, however the data were essentially subjective data. The aims were to compare an expert collective and a novice collective in basketball. Using this approach, Bourbousson, R'Kiouak et Eccles (2015) showed that the study of phenomena of interference between analysis levels could help advance the understanding of collective activity. More specifically, collective activity would arise from individual behaviour, but in return, individual performance might be undertaken in favour of a specific collective configuration. As part of this approach, the authors focused on key player roles. The results demonstrated that one specific player often had the attention of his teammates. This indicated this player had a leadership role in coordinating the team. Also, expert players had a low level of awareness of other team members. This could be explained by implicit coordination processes. Finally, in the expert team, the variability at the intra-team level was lower than for a novice team. This could be clarified by the increased ability of the expert team to accomplish and maintain a high level of awareness during the game. From a methodological point of view, this study differed from the study discussed in the 'Spatiotemporal Interference' section above in that it granted primacy to subjective data (Bourbousson et al., 2015). This work on interference between the levels of analysis justifies studying individual cognition to learn what is happening at the collective level. The step-by-step construction of individual articulation influences the characteristics of coordination at higher levels of organisation.

Criticism against actual interference. The recent studies focused on the role of interlevel interference suggest a need to investigate the correlated patterns between the individual level and the collective behaviour. However, even if we observe correlated collective behaviour, the large number of parameters in natural settings at the individual level make it impossible to draw a clear link or a real correlation between the individual and collective observations. There is a clear necessity to control the parameters experimentally to delineate the correlated behaviour. Moreover, the study of interferences should ensure that individual coordination is desired by the players. Cases of unintentional coordination (Varlet & Richardson, 2015) and spontaneous coordination (Haken et al., 1985) demonstrate that indicating a link between the levels of organisation requires precautions.

Individual regulation correlated with collective behaviour. In the literature of team-sport science, a gap remains in work that identifies correlations between individual activity and emerging spatiotemporal collective behaviour patterns. Based on dynamical system theory, collective behaviour in team sports can be explained without affording any explanation that could arise from individual behaviour. One idea to bridge the gap considers that humans are likely to be affected by the dynamics of their coordination (De Jaegher & Di Paolo, 2007), leading to emerging patterns of coordination influencing the ongoing commitment of the players. In a system, individuals are likely affected by the collective products (Bourbousson et al., 2014) they contribute to that emerge at a macroscopic level of organisation. Individuals are engaged in the process of self-organising. Agents participate in the step-by-step construction of the articulation dynamics that influence the characteristics of coordination at higher levels of organisation. To be described, these phenomena require multiple levels of analysis but also require the identification and characterization of interferences between these levels. It is this articulation of the levels of analysis that justifies the naming of a multi-level approach (Cooke et al., 2013; Kozlowski et al., 2015). If the collective level changes from one pattern to another, as shown in Haken et al. (1985), the cause should come from the individual changes. If the system is composed of many individuals, it is probable that individual spatiotemporal behaviour is related to their regulation to each other. There is a need to investigate this active regulation.

THE NEED TO INVESTIGATE INDIVIDUAL REGULATION

Over the last two decades, the non-representational approaches (e.g., the social-cognitive approach) have been focused on spontaneous coordination (e.g., the bimanual task), whereas the representational approaches have been focused on a plan for coordination (e.g., strategic planning). In this section, we attempt to demonstrate the necessity of understanding the intentional coordination that goes on within situations through individual regulation.

This research project postulates that agents regulate their individual and collective activity without a real need for symbolic representations but only by experiencing, in the phenomenological sense, their coupling with the environment. Agents are thus able to modify, adapt and transform their activities to maintain interaction with others. This purpose is mainly explained and justified in the enactive approach. We reserved the description of the enactive approach in Chapter 2, however in this section we present an overview of the idea that has been developed in sport science and in some other scientific fields as well. In the context of sport, this notion of individual regulation remains under-studied. However, the practical as well as theoretical repercussions of understanding what directs the activity of an individual in a collective are considered paramount. In line with how the enactivist approach to teamwork is applied, Bourbousson and Fortes-Bourbousson (2016) have identified the nature of the regulation of interactions performed by players in real time as a major gap in current teamwork research. Agents actively regulate their activity to elaborate and maintain the collective behaviour. Her we turn to regulation process.

Regulation required for interaction process

Regulation in interaction. Collective behaviour most often requires interpersonal coordination. This coordination is based on the interaction between at least two agents. To maintain the interaction, the regulation of the agents is absolutely required. The regulation is the way of how individuals adapt their behaviour to each other. It is defined with more details in the next section. Some studies have empirically described the fundamental function of regulation in interpersonal coordination, particularly in those using perceptual crossover (Auvray, Lenay, & Stewart, 2009). In order to highlight the minimal conditions necessary for the emergence of an interaction, Auvray et al. (2009), inspired by Murray and Trevarthen (1985), designed an experimental device to manipulate the interaction process. This device places participants in a situation in which they move an avatar into a minimal virtual environment (Murray, Trevarthen, Field, & Fox, 1985) populated by different entities (e.g., a human avatar, moving lures, and fixed decoys). No visual information is accessible, but the meeting of the entities, with the mouse, leads to a type of unique tactile stimulation that makes the encounters undifferentiated. In other words, their encounter provides the same sensory information to each other. The task for the participants is to recognize the presence of their partner and to indicate it by a click. This manipulation thus makes it possible to test the respective contributions of the interaction process and the individual information in the emergence of a coordinated interaction (see appendices for details). This device suggests that the participants succeed in recognizing themselves (i.e., one click), and thus experience their social interaction, thanks to the simultaneous and shared perception of the process of regulation that takes place. Indeed, without having any feedback on their ability to recognize themselves, the results show that the participants were relatively effective and were rarely mistaken. In keeping with this principle of regulation allowing the emergence of interpersonal coordination, most of the studies investigating this regulatory process have been experimental and have focused on coordination within dyads, providing repeated evidence of interpersonal benefits related to regulation processes (Laroche, Berardi, & Brangier, 2014).

Individual regulation in sport. In the field of sport science, it was considered that within a dyad regulation is anchored on the perception of others (R'Kiouak, Saury, Durand, & Bourbousson, 2017). This perception is the key phenomenon of interpersonal coordination and therefore collective performance. However, the majority of studies in ecological situations postulate regulation as fundamental for the emergence of social interaction without investigating it (Bourbousson & Fortes-Bourbousson, 2016). According to R'kiouak (2015), a collective elaboration is not possible without regulating the members in relation to each other. This regulation concept is developed in the enactive approach.

Enactive approach. Within the enactive approach to social coupling, researchers into the enactive approach to social coupling have assumed that each agent must take others into consideration in order to build behavioural coherence (De Jaegher & Di Paolo, 2007; Froese & Di Paolo, 2011; Gallagher, 2001, 2008). De Jaegher and Di Paolo (2007) assume that the phenomenon of emerging complex interpersonal coordination is facilitated when the two agents simultaneously regulate their ongoing interpersonal coordination (i.e., a bidirectional flow of interactions). Thus, this bidirectional activity of the agents produces a collective behaviour that exceeds the simple juxtaposition of individual productions. The need for such mutuality in interaction is also discussed as mutual awareness in other traditional research (Fiore & Salas, 2004).

Clarification regarding regulation

Collective behaviour arises from the interaction of components. *Interaction* is the general concept that explains the relation between at least two agents in a specific situation. The quality of interaction is mainly based on how players consider each other and on what will arise from these perceptions. By considering each other, interaction is maintained when agents regulate their individual behaviour to participate in elaborating collective behaviour. This regulation is divided into two parts: the *informational resources* and the behavioural *adjustment*. In real time, the way the teamwork activity of a given team member unfolds is supported by informational resources accounting for the team's dynamic behaviour – for example, what is the subject attuned to in the ongoing activity at this moment? These informational resources appear to the team member from his or her viewpoint; they are not fixed but change over time, depending on the current needs of the agent and on the unfolding events he or she is able to grasp (De Jaegher & Di Paolo, 2007). The content of informational resources supports football players' real-time spatiotemporal adjustments on the field. Adjustment is the way for an agent to behave based on significant informational resources enacted. For example, a player who is focused on a single team member, who illustrates the informational resources, attempts to maintain a stable distance from that team member over time, which illustrates the adjustment. The *regulation* appears when informational resources and adjustments support the players activity. *Co-regulation* and *active co-regulation* are two specific regulations which are described on the regulation spectrum.

Regulation spectrum

This section has been largely inspired from De Jaegher & Di Paolo (2007). Regulation manifests in different forms, which can be either observable, and accessible to third-person analysis, or more complicated within an interaction, requiring first-person analysis. When the sense-makers are interacting, we talk about a spectrum of participation ranging from the individual sense-making affected by coordination dynamics to the joint sense-making (De Jaegher & Di Paolo, 2007). All the levels in the spectrum of participation consider only two agents. The spectrum of degrees of participation is large.

Unilateral regulation. In considering the lower level of the spectrum and only one of the agents in an interaction process, the second agent can simply be a source of disruption, similar to the rest of the environmental constraints. In other words, when an agent adjusts his behaviour to follow a second agent, this second agent is not disturbed and does not react to the first agent. The first agent regulates his behaviour in the same way he would regulate it in a non-social world. Others are just objects, tools, or problems for the individual cognition. This social encounter positions only one of the two agents as interactor. The construction of meaning is an activity that remains individual: if the construction of meaning from the interaction integrates the activity of others, the converse is not true. No shared meaning is built. At best the *own world* of the interacting is modulated by the existence of the coordination.

Co-regulation. In the second degree of the spectrum participation the two agents are described as interactors. The regulation of the two agents arises from the personal interpretation of the dynamics of their coordination. However, neither of the interactors fully manages to regulate the dynamics of this coordination, whose direction seems finally to escape the interactors. The dynamics of isolated individual activities do not allow us to understand the collective dynamics resulting from their interaction. Granic (2000) described this process with the example of how interaction between parents and kids could turn sour even if there is no intention of both part (Granic, 2000). In this case, the regulation is for the first time a co-regulation. Co-regulation refers to the way in which several individuals jointly and at the same time adapt their activities to the needs of the collective situation.

Active co-regulation. Another level refers to the cases where the interactors construct shared meanings, with a convergence of these meanings towards those of one of the individuals. In this case, one of the interactors (i.e., the oriented) will move towards a new domain of meanings that was part of the significant activity of the other (the orientator). In this case, one of the agents expresses her understanding of the world with the effect of influencing the construction of meanings by the other. In other words, the former outsources her own perspective in order to guide the perspective of the second and to make the second consider the possibilities of the activity in the same way. More specifically, this case splits into two cases with increasing degrees of participation. In the first case, the oriented protagonist does not engage in regulation specifically directed towards interaction, without being passive to the extent that he engages autonomously his construction of meanings towards the world expected by the protagonist orientator. In the second case, the oriented will engage in direct regulation of the interaction, although the outcome is not changed, namely his own perspective converges with that expected by the orientator (e.g., the orientator converses with the oriented to change his affects). It is important to mention that throughout the rest of this dissertation, when regulation is mentioned it has to be understood to refer to co-regulation and active regulation.

Joint process of construction of shared meaning. Finally, at the very end of the spectrum, there is a last case in which the interactants each regulate the interaction, coordinate their significant activities, and ultimately build a new perspective that neither agent held before interaction. This case is the most sophisticated insofar as the interactants participate directly and fully in a joint process of construction of shared meanings. The interactants go beyond regulating the interaction respectively by truly engaging in a joint process of co-construction that brings out a new signifying domain (e.g., situations where the construction of shared meanings is the purpose of the collaboration: brainstorming, building a shared diagnosis, developing a participative strategy). In a way, this new domain of meanings constitutes the phenomenology of social unity, and it is irreducible to individual perspectives at the same time as it is anchored in individual activities. According to, De Jaegher and Di Paolo (2007), the circularity of action and perception conventionally used to describe the individual activity of construction of meanings here takes on a collective dimension, and sense is created through the equilibrium of patterns of joint activity. It is the highest degree of participation in the construction of meanings, and the highest degree of sophistication of the consensual domain of observable phenomena in social systems. There is some level of regulation that cannot be understood without the help of a first-person analysis. Co-regulation is said to be active when several individuals adapt in real time their respective activities to the needs they perceive for the situation.

Football - enthusiastic sport setting

Football is selected as the setting under study for several reasons. It offers a larger number of agents that can be studied, and thus, it provides greater possibilities for observing a wide range of informational resources that support real-time participants' activities.

Number of players. In the literature, the number of agents involved in the experimental design was small (e.g., two interacting agents; Alderisio, Fiore, Salesse, Bardy, & Bernardo, 2017). The investigation of dyads could limit the crucial understanding of how collective behaviours emerge from interacting individual activities. Empirical gains should thus come from investigating social systems larger than a dyad, especially by revising the regulation hypotheses. It assumed that the number of agents implied in the study design should involve changes. In the past, studies showed how varying the number of agents involved in a given collective behaviour really matters and can change the processes needed to elaborate a collective behaviour (Buchin, Giuggioli, Theraulaz, & van Kreveld, 2014). For example, the effect of the number of agents has been studied in the science of social insects. Empirical studies that investigate effects of the social system's size on the collective behaviour of humans who are regulating their online activities will contribute to a main focus of research on the topic of interpersonal coordination dynamics. Unresolved questions would need to be delivered, as investigated how many members might be required in the social system to prevent occurrences of holoptism. Football also allows the investigation of several player roles (e.g., defenders versus attackers) and their related possible spatial positioning effects. A football match is a systemic confrontation between two systems. The systems are necessarily connected to each other; the question is how agents included in these systems adapt to each other and to the constraints of the environment.

ASSUMPTIONS REGARDING VARIOUS FORMS OF REGULATION

Researchers have identified the nature of the regulation team members performed in real time as a major gap in current teamwork research (Bourbousson & Fortes-Bourbousson, 2016). This gap reveals that the description at a behavioural level of how team coordination is formed, stabilized, and destroyed is far more developed than the description of how individuals live their own interactions and regulate their teamwork in real time in relation to what they perceive as the team's behavioural needs.

The literature has made assumptions about several possible types of regulation rather than empirically describing those types. This lack of investigation contributes to an empirical-theoretical paradox, insofar as it brings into question one of the strong presuppositions of the enactive approach to social coupling, that of the need for regulation of members' activities to build the autonomy of the social system.

In line with how the enactivist approach to teamwork is applied, regulation comprises the way players adapt their own behaviour to their current lived experience of the collective joint effort and the team's needs (De Jaegher & Di Paolo, 2007).

Even if research has not focused directly on the regulation modalities adopted by the coordinating agents, previous research has made it possible to generate assumptions about the regulation modalities. Human regulation has been initially assumed to be either local or global. In this section, we also present a postulate about complex regulation and environmental regulation.

Assumption regarding local regulation

First, local regulation has been postulated in ethology (Perna et al., 2012; Perna, Grégoire, & Mann, 2014). Researchers have attempted to determine a perceptual range within termite nests. Perna et al. (2012) have identified several mechanisms; the first mechanism was called *purely local* regulation. It described the regulation of one individual to another individual from information selected in a near space that did not include information on the general state of the environment. This type of regulation was observed in many animals groups. Indeed, in many cases the animal would be unaware of the elaboration of the collective behaviour; rather, each one would be regulated by the agents around it. The arrangement of these different local adjustments would constitute the collective behaviour (Perna et al., 2012). Analogously for humans, regulation has been considered as local when an agent contributes to collective behaviour simply by adjusting to the immediate vicinity. In this case, team behaviour is explained through elementary mechanisms, suggesting it can emerge from a simple local arrangement of interactions.

Naturalistic sport setting. In sport science, some works have specified the content of local regulation. Regulation has been considered local when a team players contributes to collective behaviour while adjusting to the immediate neighbourhood (Silva et al., 2014). Local regulation is the definition applied when players coordinate by what they perceive of others' individual behaviours without considering the higher-order shapes that emerge from the interaction within the team. From this, collective behaviour is determined through simple mechanisms and arises from simple arrangements of local interactions. There is no need for players to be attuned to the overall team coordination they help develop. In the sport science literature, it is classically stated that team sport player’s coordination activity should be supported by local information, meaning information available in the player’s nearby space only. For instance, studies have investigated different variables which illustrate local regulation, by considering the interpersonal distance variability (Passos, Araújo, Davids, Gouveia, Milho, et al., 2009; Passos et al., 2011), by considering player's velocity (Passos et al., 2008) in rugby union, or by considering a player's trajectory, as in the case of an attacker–defender dyad, where it is suggested that interpersonal angles shape decision making (Araújo, Davids, & Hristovski, 2006; Passos et al., 2008) in basketball. In such works, viewing regulation as local allowed the authors to illustrate how the parsimonious processes leading to swarming behaviours observed in nature, such as in social insects or fish, can inspire sports research. It also led the authors to reinforce the relevance of affordance-based approaches to team coordination in sport, postulating that spatiotemporal sporting teamwork can unfold through elementary and nonrepresentational mechanisms.

Assumption regarding global regulation

The second regulation modality is a priori more specific to humans. Humans have the ability to regulate their behaviour from a global perception of the situation. Global regulation occurs when an agent grasps the overall state of group behaviour and adjusts his or her activity based on such high-level information. In the past, this regulation has been conceptualised in the literature that has been assumed to support the idea of collective intelligence patterns' behaviours. The concept is called *holoptism*. Holoptism appears when agents are able to grasp the dynamics of the whole system in interaction and adjust their behaviour through perceiving the given real-time joint effort. Holoptism requires a bird’s eye viewpoint. Importantly, holoptism should not be confounded with the perception of every team member's behaviour implied in the social system, which does not require a bird's eye viewpoint. A recent study illustrates this concept. People were invited to dance in a social situation. The aim was to show how participants could perform feats while being aware of the movement of all the other participants moving on a large dance floor (Long, Jacob, Davis, & Magerko, 2017). The study suggested a distinct sensibility of being aware of the individual motions of all the players on the team. Thus, there is a difference between an exhaustive local coupling and a bird's eye point of view. Empirical evidence of holoptism in human movement science has recently been described in sport science research (Bourbousson & Fortes-Bourbousson, 2016). To date, while being especially relevant to human behaviours, holoptism has not been investigated in sport, however some studies could be relevant to illustrate this concept.

Naturalistic sport setting. Such a capability for the global regulation is particularly powerful in cases in which team sport is goal directed and in which agents are concerned with monitoring the global team behaviour (Bourbousson & Fortes-Bourbousson, 2016). Some empirical evidence can be found in the literature that illustrates how a global mode of regulation can support team behaviour emergence in sport settings. For instance, expert basketball players' decisions on dribbling to the basket were shown to be better explained by global-level parameters than by local-level ones (Bourbousson, Deschamps, & Travassos, 2014), suggesting that individual players organised their activity by taking into account the global movement of players, at least in the case of the ball carrier initiating a critical action. In this type of adaptive and interactive process, the agent considers the emerging spatiotemporal form, and regulates his behaviour on this basis. Others researcher have stated that '*understanding these reciprocal relationships between the state of movement of the two dimensions of opposition (offense vs. defense) and knowing how they operate in real game-play, constitutes, by definition, tactical intelligence with regards to opposition*' (Grehaigne, Godbout, & Zerai, 2011, p.763). In this view, a given player's positioning activity is based on high-level information related to the global picture that the team achieves in real time. In road cycling, for example, riders need to have information about the overall state of the race to adjust their behaviour (Assemat, 2012).

Assumption regarding complex regulation

Third, while described to a lesser extent, some authors have proposed intermediary forms of informational resources. For instance, Perna and colleagues proposed a mode of regulation called *local estimation of global properties* (Perna et al., 2012), in which individual agents estimate the state of the global structure from information built only at a local level. For instance, termites perceived the density in an area when provided with a satisfactory overview of the current state of the overall building. This mode of regulation allows individuals to learn about the overall state from local information. For example, in termites, the local information about a chamber provides information on the general structure of the overall termite. Another complex regulation was illustrated by Marmelat & Delignières (2012). They showed that two individuals coordinating themselves with a computer-generated oscillating pendulum can coordinate by oscillating their own pendulum in a local mode but with anticipation to reduce the errors. Individuals showed an understanding of the overall dynamics of the system with which they coordinated. In sport science, complex regulation has been assumed as well.

Naturalistic sport setting. A recent study set out to understand how team members adjust their dynamic behaviour in team coordination during ongoing situation (Gesbert, Durny, & Hauw, 2017). This study sought to develop new knowledge about the regulation process by examined the regulation enacted by football player in order to be coordinated during a match. In this study, the results showed the apparition of mixed regulation. This mixed regulation was described by combining different regulation modalities or by combining similar regulation modalities. The results showed that players were able to mobilise local and global regulation at the same time. To illustrate, a defender could be focused on the nearest partner in an attempt to maintain a given distance and also on the movement of all opponent attackers.

Assumption regarding environmental regulation

All the previous regulation was based on a perception of human trajectory, movement or attitudes. Another regulation modality has considered the regulation in response to material or the environment. This type of regulation has been described in the theory of stigmergy (Grassé, 1959; Susi, 2016). Stigmergy has been described as a mechanism of indirect coordination. This coordination is mediated through the environment between agents. This phenomenon is illustrated with insect colonies. Termites leave a trace in the environment which gives information for other termites to act upon. In this way, individual traces help engender the spontaneous emergence of coherent collective behaviours. Stigmergy is a form of self-organisation; it allows collective behaviour efficiency without any need for planning or direct communication between the agents. This stigmergic process can be an effective innate way of making collective behaviour emerge and of preserving multiple players' coupling with key environmental events. Recent research in sport science has explained this form of regulation (R'Kiouak et al., 2017).

Naturalistic sport setting. R'Kiouak, Saury, Durand, and Bourbousson (2017) recently elaborated on the fundamentals of such a process in their stigmergic view of teamwork. In their study of a rowing setting, team members exhibited highly synchronised patterns of collective behaviour, achieved not by direct co-awareness of their behaviours but by exhibiting individual activities that were supported by a simultaneous awareness of their shared environment. The co-regulation of the rowers was achieved through the boat in the study setting. Such a stigmergic coordination was also investigated in other studies (Millar, Oldham, & Renshaw, 2013). In the field of sport science, the concept of stigmergy is called *extra-personal coordination*. Indeed, rowers could coordinate through shared informational resources being captured in their shared physical environment, without considering directly their respective movements.

Assumption regarding symbolic regulation

All previous regulation referred to players' adjusting their activity according to an ongoing situation rather than according to a pre-established action (Blickensderfer et al., 2010). Research has shown that agents can adjust their behaviour based on learned knowledge. In this light, the social-cognitive perspective of team coordination (Eccles & Tenenbaum, 2004) assumes that patterned teamwork mainly arises through sharing knowledge within the team, which refers to similar representations of the task and the team routines across team members. According to this approach, shared knowledge helps team members form clear expectations about others' actions so that situational probabilities can support the way each teammate behaves, rendering real-time event monitoring and related cognitive interpretation not always necessary. In other words, the agent regulates his behaviour based on this knowledge and not based on the on-going situation.

Naturalistic sport setting. Such a regulation produced in a specific team coordination process has been called *implicit coordination*. It has been assumed to be highly knowledge dependent (Blickensderfer et al., 2010). The knowledge that each team member can mobilise in the game is available so that he or she is still capable of adjusting the activity based on expectations even if he or she does not necessarily grasp the current state of the game (i.e., probabilistic events rather than situated informational resources).

DATA - INDIVIDUAL REGULATION AND COLLECTIVE BEHAVIOUR

Throughout state of the art Chapter, the aim has been to present the general concepts and findings associated with the theoretical framework in a way that would pave the road to the clear necessity for a better understanding of individual regulation. As described above, teamwork studies showed several differences in terms of the investigated objects, but these studies are also distinguishable by their method of analysis. On the one hand, teamwork behaviour was explored with behavioural data in a third-person analysis (quantitative data). On the other hand, teamwork was examined through subjective data in a first-person analysis (qualitative data). Given the need to understand how changes in player's individual regulation give rise to distinct correlates of simultaneous team behaviour, simulation data, by controlling all parameters, could prove an innovative data set to increase knowledge about individual regulation and collective behaviour.

Behavioural data - Collective understanding

From a methodological perspective, a subset of the research has been interested in the collective behaviour as unit and has described the team as a dynamical system. These researchers have focused their treatment on behavioural data (Araújo, Silva, et al., 2015; Bourbousson et al., 2010b; Clemente, Sequeiros, Correia, Silva, & Martins, 2018; Duarte et al., 2010; Memmert, Lemmink, & Sampaio, 2017; Passos et al., 2011; Travassos et al., 2010). Considering the team as a superorganism (Duarte, Araújo, Correia, et al., 2012), this research has argued that understanding the team does not require understanding how each individual behaves. However, to describe the superorganism it was necessary to collect behavioural data. In particular, relying on affordance theory (Araújo, Silva, et al., 2015), behavioural methodology offered a way to position an alternative to the social-cognitive methodology.

Tracking data. In this methodology, the behavioural data retained were mostly positional data of each individual at each moment. This approach requires collecting position data using GPS capture systems. Researchers have used the ProZone analysis system to track the movements of the 20 players in a football match (Vilar, Araújo, Davids, & Bar-Yam, 2013). With the help of tracked positional data, research revealed how players and teams interact during competition (Filipe Manuel Clemente et al., 2018). A manual system, called *Tacto*, has also been developed to track the positions of the players based on a video recording (Duarte et al., 2010). This software has been validated to quantify player movement in football (Serrano, Shahidian, & Fernandes, 2014). This methodology allowed the recording of the positions of players and the study of all metrics based on these positions at every moment.

Metrics. Based on this positional data, team behaviour has been analysed with the help of metrics. These measures are classed into four major categories. The first category is a measure of the team centre. Team centre characterises the relative positioning of one or both teams within all movement displacement. A team's centre is determined by calculating the mean lateral and longitudinal coordinates of all players. In some cases, not all players contribute equally to this measure that involve changes in the equation. Team centre allows the evaluation of the intra- and inter-team coordination in team sport (Bourbousson et al., 2010a; Frencken, Lemmink, Delleman, & Visscher, 2011). To understand the collective activity by considering the team as a unit is to associate the team with its behavioural characteristics. Thus, Mc Garry (2009) states that the team as an entity can be reduced to the variability of its centre of gravity and the variability of its stretch index.

The second category is measures of team dispersion. Team dispersion is defined by the stretching and expanding of a team. The collective behaviour is captured by measures that evaluate the spatial dispersion of players, such as the stretch index, the team spread, and the surface area. The stretch index corresponds to the contraction and reduction of distances between players of a team the team centre. The surface area illustrates the smallest size of a zone that includes all team members (Clemente et al., 2013). In one study, researchers measured the collective behaviour of two opposing teams. They compared two situations, one with ball possession and one without. The results showed significant differences between the two situations in the stretch index and the surface area.

The third category concerns team synchrony. Several tools have been used to assess coordination between two oscillatory units. For example, the phase relations of two rowers can be measured to illustrate a type of synchrony (Feigean, R'Kiouak, Bootsma, & Bourbousson, 2017). The phase synchronization of two signals has been also studied in team sports through relative phase analysis (Bourbousson et al., 2010a,b) and running correlations (Frencken et al., 2012). Frencken et al. (2012) aimed to study inter-team distance synchrony related to events during the game.

The final category concerns the labour division (e.g., Voronoi diagrams, dominant regions, heat maps). The idea is to illustrate the individual effectiveness of the players within the collective behaviour. For example, a Voronoi diagram is used to partition into regions all the individual zones. It is based on distance to others on the field, including opponents. In the study of football, research has examined the spatial dynamics of team sports determined by Voronoi diagrams (Fonseca, Milho, Travassos, & Araújo, 2012).

Subjective data - Individual understanding

Some research has apprehended collective behaviour with the help of subjective data (Bourbousson, Poizat, Saury, & Sève, 2012; Poizat, Bourbousson, Saury, & Sève, 2009; Poizat et al., 2009; Poizat, Sève, & Saury, 2013). The analysis of subjective data was conducted primarily with reference to the paradigm of enaction. Subjective data is needed because enactive approach involve the collect of this type of data. Enactive approach considers an asymmetrical coupling of the agent with his or her environment. This coupling induces humans to bring out their *own world*. If everyone lived in their specific *own world*, then it would not be possible to understand the world of any agent except through the agent's description of it. The subjective data describes the world in which the agent lives. Interpersonal coordination can be analysed from the subjective viewpoint of the agent without trying to understand the behaviours from an outside point of view (Bourbousson et al., 2012). In sport science, such enactivism has been fruitful in showing how qualitative descriptions of sport activities offer a counterbalance to current behavioural theories (Poizat et al., 2013; Rochat, Gesbert, Seifert, & Hauw, 2018; Rochat, Hauw, Philippe, Roten, & Seifert, 2017). Regarding teamwork investigation, the method has been mobilised in the analysis of the joint action of rowers (R'Kiouak, Saury, Durand, & Bourbousson, 2016), basketball players (Bourbousson, Poizat, Saury, & Sève, 2012), and table tennis teammates (Poizat, Bourbousson, Saury, & Sève, 2009). The results have revealed a variety of patterns in term of attacker-defender interaction.

Interviews. Subjective data are collected from the self-confrontation of an individual to the traces of the lived situation. The goal of the self-confrontation interview is to gather verbalizations that will be analysed later. Dealing with subjective data requires questioning the agent about his or her experience in the situation. The self-confrontation interview (Theureau, 2003) is a methodological tool that makes it possible to analyse subjective data. The explanation interview is another such tool (Vermersch, 1999). The enactive approach proposes that team coordination processes has to understand by reconstructing how individual cognitions' articulate within performance environments and by determining how these articulations are adjusted, step-by-step, over time.

Thematic analysis. Some research has used these interview methods to investigate the collective dimension of an activity. Poizat et al. (2009) sought to understand collective activity in table tennis by using verbalization data to account for doubles partner sharing information in a doubles situation. This study advanced the understanding of the way in which contextual information is shared by players in a game situation. Other studies have been carried out, notably in basketball, to report on the dynamics of player–player dyads (Bourbousson et al. al., 2010a) and to report the networks (Bourbousson et al., 2012) and to report the dynamics of sharing concerns from subjective data (Bourbousson et al., 2011). Note that this methodology does not refuse to address behavioural data in cases where they provide subjective insight, but primacy is granted to subjective data. It is also possible to mix phenomenological data and behavioural data (R'Kiouak et al., 2017; Saury, Adé, & Seifert, 2016). Different tools are used to analyse subjective data. Given the needs of the current project, thematic analysis seems to be the most promising approach (Braun & Clarke, 2006; Braun, Clarke, & Weate, 2016). Thematic analysis is a method commonly used to analyse subjective data in sport science (Doron & Bourbousson, 2017). Moreover, this type of analysis allows for better generalisation of its results (Smith, 2017).

Innovative data - Modelling and simulation

The need to understand how humans regulate their behaviour is associated with descriptions of consciousness and thus with the need for subjective data. However, to gain insight into how changes in players' individual regulation gives rise to distinct correlates in simultaneous team behaviour, we also need behavioural data. Some studies have used a combination of data to better explain the interreference between the levels of analysis (Bourbousson et al., 2015; R'Kiouak et al., 2017). These studies, however, collected data in natural sport settings, which does not allow for control of all parameters. As a consequence, the link between the micro-level and macro-level of analysis cannot be definitively proven. In sport science, it could be useful to control the regulation of the individual player to observe the correlate collective behaviours. No study has used such a design in sport science, although it has been applied in studies in other fields. Applications exist in particle physics for studying elementary particles in this way, in chemistry for studying molecules, in robotics for studying actual robot implementations, in cell biology for studying cells, and in ethology for studying animals. All these fields have studied the emergence of behaviour from a multi-agent system. In this case, the agent can be either a particle, molecule, robot or human.

***Simulated data*.** Many team sports, such as football, describe structural order, with the behaviour of the organisms, the team appears to move as a unique coherent unit. Collective behaviours could be understood by considering the lot of interactions among players. From a methodological perspective, to observe relationships between the individual regulation and collective behaviour levels requires controlling all parameters so that just the regulation parameter can be varied. In ecological situations, controlling all parameters is very difficult, and thus there is not certitude for explaining a direct correlation. For this reason, elaborating a simulation model seems to be a satisfactory choice for studying the interdependence between the individual level and the collective level.

Multi-agent model. Individual-based computer simulations are demonstrated as useful analytical tool for studying group behaviour. With the simulations showed that hierarchical control and global information are not always essential to elaborate effective collective behaviour (Couzin, Krause, James, Ruxton, & Franks, 2002). The basic models of collective movement suggest that individuals move at a constant speed and suggest the global direction of motion are executed within their local neighbourhood. Simulation models are particularly useful because the minimalism allows them to be analysed using techniques developed for physical systems (Couzin et al., 2002). Multi-agent systems, by contrast, are used to simulate interactions between autonomous agents. Researcher seek to determine the evolution of such systems to predict the results. Simulation studies allow for control all individual parameters and allow us to clearly evaluate what we want. This local-to-global approach often deploys multi-agent simulations of collective behaviour, in which the goal is to reproduce characteristic global patterns by modelling the behaviour of simple agents. A less common, but equally important, approach is global-to-local analysis. The goal is to observe patterns at the global level and use them to infer properties of agents and their interactions at the local level. In sport science, insight into how changes in players' individual adjustments give rise to distinct correlates in simultaneous team behaviour has not been demonstrated in the past.

CHAPTER 2 - SCIENTIFIC GAPS

The state of the art review revealed the large contributions that have been made in the scientific literature to understanding collective behaviour. However, some areas for investigation have been neglected. To this end, in this Chapter we present the essential gaps that could be interesting to bridge.

REGULATION IN LARGE GROUPS IN NATURALISTIC SETTINGS

Presupposed vs investigated. Bourbousson and Fortes-Bourbousson (2016) have stated a lack of understanding of the nature of individual regulation. They considered that the regulation has been presupposed rather than investigated. This regulation defines the way players adapt their own behaviour to their current lived experience of the collective joint effort and the team's needs (De Jaegher & Di Paolo, 2007). The gap reveals that the description at a behavioural level of how team coordination is formed, stabilised, and/or destroyed is far more developed than the description of how individuals live their own interactions and regulate their teamwork in real time in relation to what they perceive as the team's behavioural needs. In real time, the way the teamwork activity of a given team member unfolds is supported by informational resources accounting for the team's dynamic behaviour (i.e., what is the subject attuned to in the ongoing activity in this moment?). These informational resources appear to the team member from his or her viewpoint; they are not fixed but change over time, depending on the current needs of the agent and on the unfolding events he or she is able to grasp (De Jaegher & Di Paolo, 2007). However, informational resources supporting an individual's contribution to collective behaviour have more often been theoretically presupposed (i.e., as they were in the ecological dynamics and social-cognitive frameworks) than empirically investigated (Bourbousson & Fortes-Bourbousson, 2016, p. 201). No study has investigated precisely the informational resources necessary for the interaction. A fine and complex understanding of the extent of these informational resources, their conditions, possibilities, and how they help to understand stable collective behaviour is a significant topic to be investigated.

Experimental vs naturalistic. When attempts were made to empirically describe the nature of the informational resources supporting individual activity, those resources were experimentally manipulated. For example, in a study of a dual-rocking-chair, coordination tasks were controlled by allowing the agents to see or not see each other, with researchers observing the subsequent effects on interpersonal synchrony of their manipulation of informational resources (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). Interestingly, another study compared the effects of individual activities being supported by informational resources at either a local (i.e., limb motion) or a more global level (i.e., optical expansion) of perception within dyads (Meerhoff, De Poel, & Button, 2014). First, participants had to follow, in order to keep the initial separation distance, a virtual display of both segmental (limb motion) and global (optical expansion) motion information. Second, they had to follow a sphere in which segmental motion information was absent. The results suggested that coordination can be successfully guided by global information. However, the segmental movement information allowed more adaptations (Gipson, Gorman, & Hessler, 2016; Schmidt, Carello, & Turvey, 1990; Schmidt & O'Brien, 1997). Despite these findings, there is still a relevant debate in the scientific literature about the need to study phenomena and processes of interaction in situ. Indeed, interpersonal coordination is considered to be complex behaviour that includes many constraints that influence the possibilities for interaction and which cannot be fully reproduced or considered in the laboratory. No study has investigated precisely the individual regulation necessary for interaction in naturalistic sport settings.

Dyad vs large group. According to Bourbousson and Fortes-Bourbousson (2016), the study of individual regulation supporting team behaviour should consider the number of agents. In the past, many studies have investigated team coordination in dyads in situ (Passos et al., 2011) or with an experimental design (Marmelat & Delignières, 2012). The number of agents implacted in the experimental paradigms was quite small (e.g., two interacting agents). Studying dyads have restricted the fundamental understanding of how collective behaviours emerge from interacting individual behaviour. Moreover, these studies were probably not able to capture the complexity of interacting behaviour in larger social systems, such as football, especially with respect to questions about the local versus global nature of the regulation. To investigate the possibility of global regulation (Bourbousson et al., 2014; Marmelat & Delignières, 2012; Perna et al., 2012), it seems interesting to investigate very large collective behaviour. For example, fans perceive the movement of a Mexican wave in the stadium and regulate their oscillations based on the global movement (Bourbousson, 2015). Furthermore, the investigation of local and global informational resources should benefit from the study of large groups, due to the levels of group organisation being better distinguished in such groups.

INDIVIDUAL ACTIVITIES AND THEIR CORRELATES IN COLLECTIVE PATTERNS

Individual vs collective level. The collective behaviour process is described at different levels of organisation (e.g., dyad, sub-group, team). For instance, one study (Bourbousson et al., 2015) has investigated shared awareness within a social network at different levels of analysis. The result described the social network proprieties at the level of the team and at the level of triadic and dyadic levels. Also, a recent study in basketball has described interference between the levels of organisation (Bourbousson et al., 2014). The result showed that, for the drive, there was variation among the collective constraints. In other words, the individual activity of triggering a drive was anchored in a destabilization of collective forms emerging from the coordination of individual activities. This suggests relationships between the levels of organisation, which also suggests that each level could potentially influence the others. The individual level can impact and modify the level of collective behaviour. However, in the field of spatiotemporal behaviour research, there is no study that has clearly investigated the correlation between individual regulation and the collective consequences that appear at the level of team behaviour.

Spatiotemporal vs subjective approach. Interference between the levels of analysis has been demonstrated according to the spatiotemporal approach (Bourbousson et al., 2014) and according to the subjective approach (Bourbousson et al., 2015). The ecological approach also affords the possibility of describing patterns of collective behaviours. These patterns are characterized using computational metrics for team analysis (Araújo, Silva, et al., 2015; Filipe Manuel Clemente et al., 2018). Although patterns may be acceptable to explain a part of team behaviour, they cannot describe all its properties. Indeed, imagine a human going to work every morning at the same time in parallel with a neighbour who leaves the house 20 minutes later every day to go to work. For a researcher using a third-person (Petitmengin, 2006) perspective, a pattern can describe a perfect synchrony between these two individuals. Neither of the individuals, however, can explain this coordination, simply because the coordination is accidental. Thus, to show the non-accidental nature of observations, a qualitative analysis of the intentions and actions of the individual is needed. The enactive approach affords the possibility of understanding the individuals' activities based on the individuals' experience when contributing to the collective behaviour. However, comprehension of collective behaviour cannot be complete with only a qualitative approach. In other words, there is a need to combine the quantitative data and qualitative data to understand collective behaviour as fully as possible. No recent study has tried to mathematize the qualitative data to increase the power of generalization of the results. Simulation models could be a useful method to bridge this gap. In the field of the spatiotemporal behaviour research, there is no clear study which generates data from simulation model that is based on subjective data (Bourbousson et al., 2014) and models it. This method could improve the knowledge about both bottom-up and top-down flows that exist in all complex systems (Gipson, Gorman, & Hessler, 2016).

MANAGING INDIVIDUAL REGULATION

Changes in individual regulation could influence the correlate collective behaviour patterns. This expectation gives rise to another objective. Indeed, if collective patterns are predictable based on individual regulation, the control of individual regulation could afford new possibilities for obtaining the expected team behaviour. For example, when a player attempts to maintain a distance from another agent, this player has more opportunity to be locally than globally regulated. However, it seems necessary to first delineate the regulation. In fact, the regulation is constituted by informational resources and individual adjustment. It has been postulated that, at this step, the local information resources result in a local adjustment.

However, Perna et al. (2012) have shown that local information resources could instead give an overview of the global shape of the collective behaviour. For this reason, there is a need to investigate the link between the informational resources and the adjustment modality.

Delineate regulation. Based on the results demonstrated by Perna et al. (2012), an investigation in football could offer several possibilities for regulation. Considering only the local and global regulation assumes that the information resources could be either local or global and the resulting adjustment could be either local or global. In other words, it is possible to obtain, (1) local adjustment based on local informational resources, (2) global adjustment based on local informational resources, (3) local adjustment based on global informational resources or (4) global adjustment based on global informational resources. No study has delineated regulation with this level of detail.

Interaction rules. One objective is clearly to produce the collective behaviour expected. The control of individual regulation (e.g., adjustment) could allow the realization of this aim. The control of individual regulation could emerge from the interaction rules given to agents. For instance, a rule to maintain the same speed as the nearest player could involve local adjustment, whereas a rule to maintain a square shape with four other agents could involve global adjustment. Further questions arise from the interaction rules. What is the viability of situations in which there is heterogeneity of the regulation modalities? That is to say, do partners simultaneously adopt distinct modes of regulation? What are the conditions under which these modes of regulation occur?

EPISTEMOLOGICAL NEEDS

To bridge all these gaps, we need to switch from the traditional epistemological approach. Indeed, the literature review described several criticisms of the social-cognitive approach and the ecological dynamics approach. Based on its focus on the shared knowledge hypothesis (Silva et al., 2013), the social-cognitive approach misses the ecological character of the sport situation. The ecological approach, by considering the collective behaviour as a unit, misses the lived experiences of the individual in the elaboration of team coordination. For these reasons, the present investigation of individual regulation modalities should go beyond these approaches and use an innovative approach that could afford the possibility of bridging all the gaps.

Need for enactive approach. Currently, there is no epistemological concept capable of theorising the way in which an individual regulates his or her activities in a sport setting. The enactive approach, however, by considering the lived experiences of individuals, the importance of the ongoing situation, and the role of the interaction itself and by making use of dynamical system theory.

CHAPTER 3 - EPISTEMOLOGY - ENACTIVE APPROACH

We identify five core ideas that define the enactive paradigm. These are the mutually supporting concepts of autonomy, sense-making, embodiment, emergence, and experience. (De Jaegher & Di Paolo, 2007, p.487)

Introduction. The previous chapter demonstrated gaps in the previous research and argued for the importance of investigating how individuals regulate their individual behaviour to the ongoing situation so as to participate in the collective behaviour. Moreover, the literature has shown a theoretical lack of understanding of the individual regulation processes. To this end, we suggest use of the enactive approach (Maturana & Varela, 1980) to theoretically justify the investigation of individual regulation. The theoretical framework developed by Maturana and Varela (1980) introduced the idea that, during their lived experience, individuals construct their own perspective on the world. The theoretical framework defended by De Jaegher and Di Paolo, (2007) was part of this enactive approach and was interested in the interaction process between individuals in a social encounter. This part of the framework is of particular interest for supporting team behaviour research.

Chapter overview. This chapter presents an overview of the enactive approach as a guideline to help future researchers better understand this approach. We aim to give a step-by-step explanation that will help the reader to follow the argument. We voluntarily include citations in this part to avert misrepresentation of the nature of the enactive approach and to avoid misunderstanding.

Quintessence. Before providing details and explanations, we first summarize here the path of thought that led to a belief in the enactive approach. First, the enactive approach delineates a specific conception of human activity. Based on the biologic foundation of a living system, the enactive approach considers human autonomy to be that which defines the human's identity. This autonomy constitutes the structural coupling between the agent and the environment. Structural coupling designates that humans are indivisible from their environment, from which emerges a significant *own world*. This own world admits that each individual manages his or her self-regulation within the environment. The enactive approach also considers the possibility of social cognition with a focus on the interaction process itself, on the autonomy of social interaction and on the sense-makers interacting. This enactive social cognition perspective allows application to collective behaviours, notably through dynamical system theory. To conclude, the enactive approach resorts to human phenomenology by considering the pre-reflective self-consciousness.

ENACTIVE HUMAN ACTIVITY CONCEPTION

Indeed, we will propose a way of seeing cognition not as a representation of the world 'out there', but rather than as ongoing bringing forth of a world through the process of living itself. (Maturana & Varela, 1987, p.11)

This section delineates the human experience as traditionally understood from the cognitivist perspective. The cognitivist conception of human activity has been discussed as not focusing sufficiently on situated nature. Cognitivist research has not considered the embedded and embodied nature of human cognition (Froese & Di Paolo, 2011), and recent research has commonly rejected the representational approaches to cognition. This research denies that cognition relies on representations (i.e., symbolic) of a predetermined external world (Varela, Thompson, & Rosch, 1991). More precisely, the enactive approach does not deny the ability of individuals to produce mental representations, but challenges the central role attributed to these representations in the explanation of cognition and of the adaptation of individuals to their environment (Maturana & Varela, 1980; Maturana & Varela, 1987; Varela et al., 1991). The enactive approach has been constructed on a strong biologic foundation.

Biological foundation of a system

Living system. By definition, a system is composed of components and their interactions within the living system itself. Two main concepts define the living system: the organisation and the structure (Maturana & Varela, 1987). Organisation refers to the relationships that must exist between the components of a system to be a member of a given class, while the structure designates the components that constitute a particular unit. Structure is the embodiment of this organisation. A system can be either non-cognitive, such as a robot, or cognitive, such as a human (Di Paolo & Thompson, 2014). All the enactive approach concepts developed in the next section concern only cognitive systems.

Autopoiesis. As described before, each system has an organisation. The specific organisation of the living system is its autopoiesis (Maturana & Varela, 1980). Autopoiesis is the minimal organisation of a living system which describes biologically the self-production of a single-cell organism (Maturana & Varela, 1987). Living systems are autopoietic in the sense that they retain their organisation, at the cost of structural transformations in response to the disturbances in their environment. All autopoietic systems have been described as operationally closed (Di Paolo & Thompson, 2014).

Operational closure. The particular organisation of the living and autopoietic system (i.e., relationships and processes are maintained between physical components) ensures a regeneration of the component and maintains a physical space delimited by a dynamic frontier. In other words, due to the activity of the different processes, the system is clearly self-enabling and it sustains itself in time (Di Paolo & Thompson, 2014). Such a self-enabling system is described as an operationally closed system. All living systems defined by autopoiesis and operational closure are characterised by a constitutive autonomy.

Autonomy. As the point of its foundation, the enactive approach adopted the concept of *autonomy*. The autonomy of the system allows for the development of an individual's own identity (Froese & Di Paolo, 2011). The activity of the system is both the cause and the effect of the autonomy. The activity of the system depends on organisational constraints. The autonomy of a system corresponds to its fundamental capacity to be and maintain its organisation, that is, its *identity*. Thus, the agent is subject to continuous structural changes that result from interactions with the environment in which the agent evolves or from its internal dynamics. This autonomy describes the fact that a living system self-constitutes its identity. Finally, autonomy makes agents more or less sensitive to certain disturbances of the environment, and it is what characterizes the coupling between agent and environment.

> *Without the autonomy afforded by organizational closure the system is incapable of defining its own identity as an individual; it remains an externally defined collection of components that we have merely chosen to designate as an 'agent' by convention. (Froese & Di Paolo, 2011, p.6)*

Emergence of a significant world

The autonomy of the living system allows maintenance of the organisation regardless of the constraints. The constraints affecting the organisation are either internal dynamics constraints or specific environmental constraints. The impact of constraints of the environment could specify the dynamics of the transformation of the living system (i.e., the human).

Structural coupling. The enactive approach considers that the individual is inseparable from the world in which he or she is physically engaged, thus cognition emerges from this interaction between the living system and its environment. The relation between living system and environment has been defined as a structural coupling (Di Paolo & Thompson, 2014; Maturana & Varela, 1987). The structural coupling is described at different levels of organisation (Fig. 1). Three orders of couplings are defined (Maturana & Varela, 1987). The first-order coupling describes the interaction between an autopoietic system and its environment. For example, biologic cells illustrate this form of coupling. The second-order coupling is defined by the interaction between an autopoietic system with a nervous system and its environment. A third-order coupling involves a combination of two second-order systems. In a third-order coupling, an organism with a nervous system interacts with another, thus organisms live in interaction. Third-order coupling is a universal phenomenon that appears in different animal groups under a variety of forms. This coupling also describes human activities.

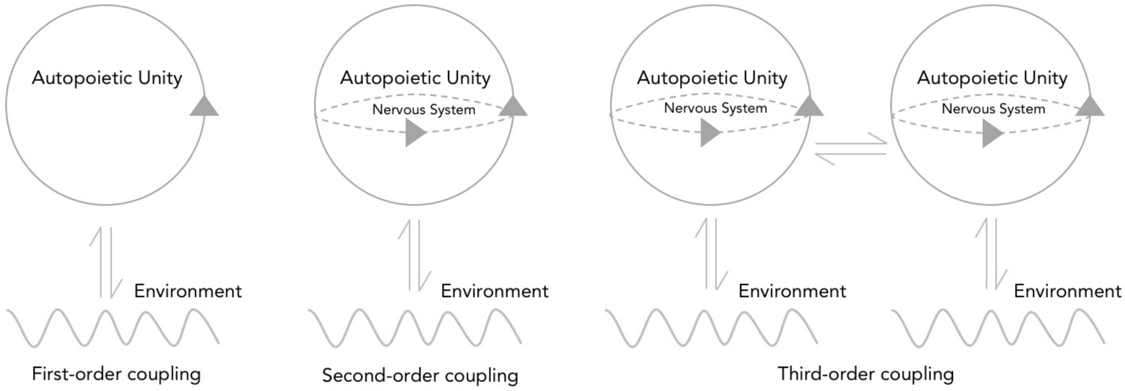

Figure 1. Illustration of the three orders of couplings. The first-order coupling describes the interaction between an autopoietic system and its environment. The second-order coupling is defined by the interaction between an autopoietic system with a nervous system and its environment. The third-order coupling describes the interaction of an organism with a nervous system with another such organism.

Asymmetrical coupling. Another key aspect of the structural coupling between the agent and its environment is the *asymmetry*. In another words, the individual only interacts with those characteristics of the environment that are relevant or that produce disturbances on its internal dynamics. For example, research has shown that animals and humans identify different relevant characteristics in a living room (Von Uexküll, Von Uexküll, & O'Neil, 2010). For humans, all the objects have relevant characteristics, whereas for flies, all the different objects have quite the same significance (Fig. 2). This significative difference between the relevant characteristics can also be illustrated between human themselves.

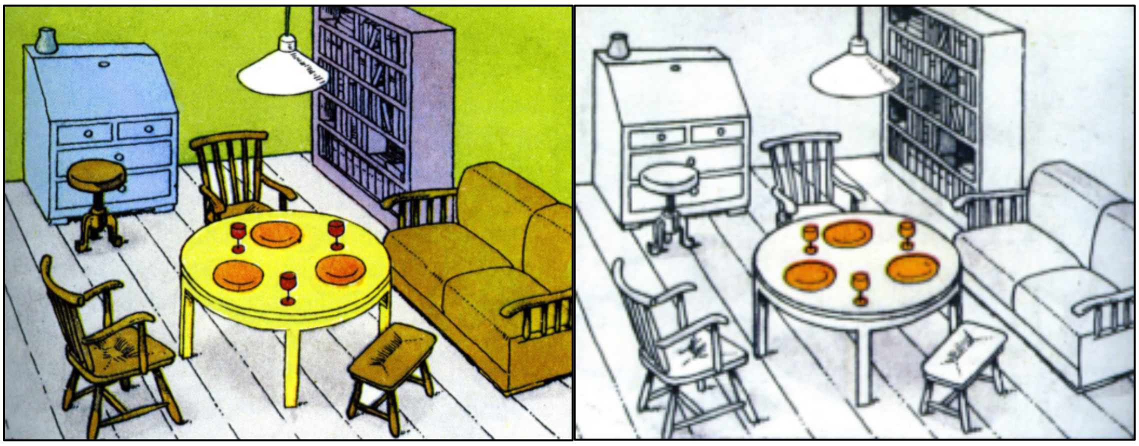

Figure 2. Illustration of the construction of significant characteristics for a human (left) compared to a fly (right) in a living room. Each colour represents one meaning, in other words, all the objects have different meanings for the human, whereas for the fly, the living room affords only two meanings.

The coupling is asymmetrical due to the fact that it is based on the perspective of the human. Individuals are not constrained to a prescriptive disruption of the environment but could be described as *selecting* their own perturbations. In any case, it is not the individual as an individual who selects the disturbances but perhaps, rather, the internal organisation of the individual that conditions the selection of sources of disturbances. Individuals interact with a part of the environment to maintain the activity of the internal organisation. Therefore, if each human enacts different significant characteristics on the surrounding environment, it is common to say that each individual has his or her *own world*.

> *There is an asymmetry underlying the relational domain of an autonomous system since the very existence of that relational domain is continuously enacted by the endogenous activity of that system. (Froese & Thompson, 2011)*

Own world. The concept of asymmetrical coupling implies that each individual, through its internal organisation, specifies its own constraints and perturbations in the environment. One disruption from the environment enacts an own world for each individual. The system delimitates its own space of disruptions. The own world refers to the idea that humans experience ongoing situations differently. Therefore, the own world is described the fact that the human activity is embedded and embodied in it (De Jaegher & Di Paolo, 2007). The own world is conceptualised in the enactive approach by *sense-making*.

Sense-making. The enaction approach considers that there is a meaningful world for the autonomous human system. From asymmetrical coupling emerges meaning. Sense-making is the relational process of signification between an autonomous, self-organising agent and his or her world. Sense-makers always have a certain perspective on their world because their self-organisation entails certain needs and constraints. The exchanges with the environment are thus fundamentally significant for the agent, and cognition emerges from making sense. *Sense-making* refers to the idea that the agent does not passively receive information from the environment but constructs the meaning actively. Making sense refers to the enaction of a significant world by an autonomous system (Froese & Di Paolo, 2011). The notion of sense-making is the process of meaning generation in relation to the concerned perspective of the individual (Weber & Varela, 2002). This concept tends to make the situated experience as lived by the agents the condition for characterising how individuals operate in their real-time activity. This description of sense-making suggests that individuals could regulate their behaviour based on sense-making.

> *'Sense-making' describes behaviour or conduct in relation to norms of interaction that the system itself brings forth on the basis of its adaptive autonomy (Di Paolo & Thompson, 2014)*

Self-regulation of the coupling

Adaptivity. Living systems, by definition, act in a way to maintain the viability of their organisation. To perpetually accomplish this function, they preserve structural coupling through regulation. This regulation refers to what is called adaptivity. Adaptivity describes the fact that change in the structural coupling contributes to maintaining a portion of the processes that constitute an agent (Barandiaran, Di Paolo, & Rohde, 2009). In other words, adaptivity supports the fact that the own world of a living system is a construction and transformation of meanings (Di Paolo, 2005). Adaptivity is defined as '*a system's capacity, in some circumstances, to regulate its states and its relation to the environment'* (Di paolo, 2005, p.438). According to Froese and Diapolo (2011), two criteria are inherent in the property of adaptivity: to improve their situation, humans must be able to determine how the structural changes are fitting their movement within the viability, and humans must have the capacity to properly regulate the conditions of their movement. Adaptivity is explained as a set of internal regulatory mechanisms that can be deployed involved at the boundary of the organism (Di Paolo, 2005). Adaptivity allows the living system to recognize its encounters, however, adaptivity in not sufficient for allowing an organism to act in response to these encounters. To better accomplish the active regulation of the agent, we have to define agency.

> *Adaptivity refers to the ability of certain autonomous systems to regulate their operationally closed processes in relation to conditions registered as improving or deteriorating, viable or unviable* (Di Paolo & Thompson, 2014, p.6)

Agency. At the next level of self-regulation is agency. Agency of the individual is the capacity to interact with the individual's own world. In other words, agency refers to the ability for an autopoietic organism to feel the effects that it has on the environment. To do that, the agent must actively regulate its behaviour according to the effects perceived. Active regulation is therefore based on the asymmetry of the coupling between an agent and its environment. Agency exists in the dynamical interaction between an agent and its environment (Stewart, Gapenne, & Di Paolo, 2010). The challenge of active approach is to write the way in which individuals actively regulate their activity based on what is meaningful to them. Agents regulate their activity, relying on particular experience they have acquired with a given activity. Froese and Di Paolo (2011) *'put forward a definition of agency which holds that an agent is an autonomous system that adaptively regulates its interaction with its environment and thereby makes a necessary contribution to sustaining itself under precarious conditions' (Froese & Di Paolo, 2011).* Froese & Di Paolo (2011) point out a major difference between adaptivity and agency. Whereas adaptivity refers to an internal organisation of constructive processes, agency describes the regulation of extended sensorimotor adjustment.

To conclude, the concept of agency is announced as a basic form of an autonomous system's social life.

> *The term 'agency' refers to the ability of an autonomous system to achieve adaptation not only via internal re-organization, but also by adaptive regulation of its sensorimotor interactions. (Froese & Di Paolo, 2011, p.4).*

Zombie and baby experience. Adaptivity and agency are specific to living systems, and two experiences could illustrate perfectly their definitions. The experience of the zombie is an explanation of the concept of the adaptivity (Thompson, 2011). Indeed, a zombie is a body that is physically similar to a human. However, a zombie can only be disturbed by the environment without having the possibility to act on it. A zombie can regulate his behaviour but not actively regulate his behaviour. For this reason agency is not conceivable for the zombie. In contrast, in a recent article, Kelso (2016) defines the notion of agency with an illustration of a baby (Kelso, 2016). According to Kelso (2016), a baby is born with only spontaneous movements (as a zombie). As babies grow up, however, their movement causes changes in the world. Babies discover that they can act on their environment as a causal agent. To demonstrate this assumption, researchers coupled the baby and a mobile with a rope attached on the one foot. They showed that when the baby was coupled, there was a significant increase in the activity of the leg, whereas when the bay was uncoupled, the activity of the leg decreased. The experience of the baby is an explanation of the agency. To conclude, the behavioural diversity in the capacity for regulation illustrates the human cognitive conception of the enactive approach (Fig. 3).

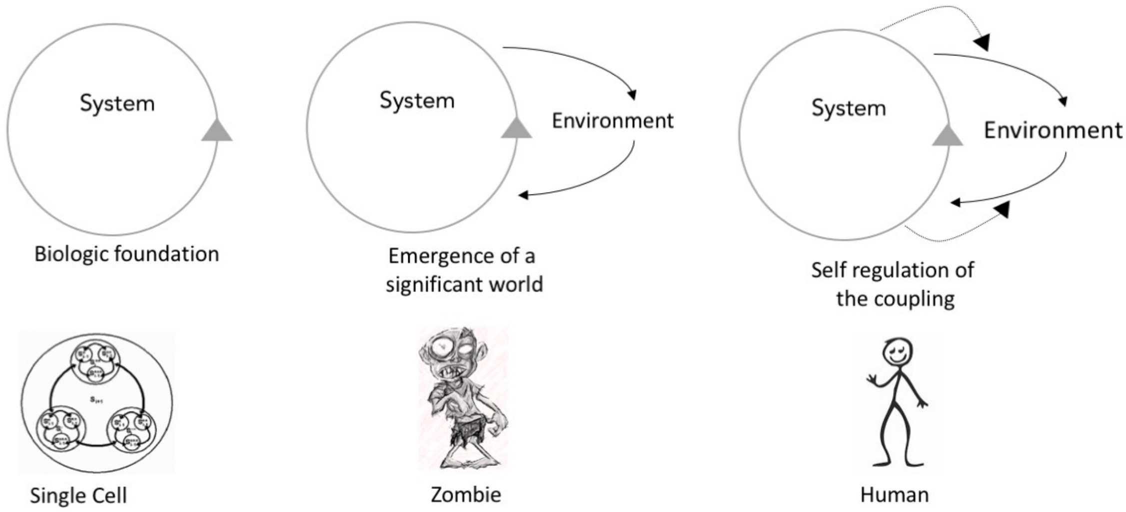

Figure 3. Illustration of the enactive human conception. Three levels are represented: the cell, which is a system; the zombie, which is a system coupled with the environment; and the human, which is a system coupled with the environment and with the capacity to self-regulate the coupling.

Links with dissertation. The enactive approach seeks to understand a significant dimension of human activity – how meanings are enacted. Active regulation (Fig. 4) occurs when an individual act on his or her own coupling to allow significant meanings to emerge. When this regulation is done in a social environment, individuals show behavioural adaptation that reflects the experience they have of the collective activity rather than the whole of their own activity. Any co-regulated collective activity engages the subjectivity of the actors. The enactive approach has described human cognition and has also considered the enaction of social cognition. This recommends that team coordination processes should be investigated by reconstructing how individual cognitions are articulated within performance environments and by determining how these articulations are adjusted, step-by-step, over time.

SOCIAL COGNITION

In our opinion, any approach that mentions interaction, but fails to go into the relational dynamics of the interaction process in detail, is simply not an interactive account and probably not even a social one, despite the goodwill driving it. (De Jaegher & DI Paolo, 2007, p.494)

With the aim of improving our knowledge about how team behaviour works, it seems necessary to adopt a theoretical approach to matters in social cognition. The social-cognitive approach to teamwork neglected the key role of ongoing interactions in patterning collective behavioural states (Cooke et al., 2013), an omission which cannot fit with the conception of the autonomy of human activity. The enactive principle on human activity has been adopted here for our discussion of interaction between agents. In contrast to the agent/environment coupling, in which only the agent is autopoietic, a social coupling (i.e., a third-order coupling) indicates interaction occurring between at least two autopoietic units. Both autonomous units delimit their own area of disturbances.

A focus on interaction processes

Social interactions are mediated by the coupling between at least two autonomous agents (Maturana & Varela, 1987), *'where the regulation is aimed at aspects of the coupling itself, so that it constitutes an emergence autonomous organisation in the domain of relation dynamics, without destroying in the process the autonomy of the agents involved'* (De Jaegher & Di Paolo, 2007, p.493). Given that interactions between several embodied agents cannot be reduced to the individuals' behaviour, emergence of interaction in the social domain is appropriate. The enactive approach suggests that team coordination processes should be analysed by reconstructing how individual 'cognitions' articulate with performance environments and by determining how these articulations are adjusted step-by-step over time (Withagen, De Poel, Araújo, & Pepping, 2012). For instance, adaptive agents share an environment; if one agent acts in an environment, another agent could be disturbed. Although several theories consider the role of the human interaction as embodied, these theories have focused on the individual and not on the interaction process itself. In the enactive approach to social cognition, interaction is a cognitive process itself (De Jaegher et al., 2010) and not reduced to a facilitating process for human activity. According to De Jaegher and Di paolo (2007), the enactive approach describes the interaction as *constitutive of social cognition*.

As evidence of the key role of the interaction process itself between individuals in their social activity, De Jaegher and Di Paolo (2007) described the experience of Murray and Trevarthen (1985), in which a child and his mother interacted live via interposed video screens. The authors showed that if the behaviour of the mother was suddenly replaced by a recording captured earlier in the same interaction (meaning the child was thus deprived of the situated interaction), the child immediately became disturbed and lost interest in the screen. Seen in this way, it is not all facets of the expressiveness of the mother or the adequacy of the video representation of the mother that makes the communication interesting for the child but the situated process of interaction itself, which is from a very early age constitutive of human sociality. Social interaction is therefore a level of analysis that must be considered on its own.

Autonomy of social interaction

***Precarious autonomy*.** The precarious character of the third-order couplings comes from the changing nature of their autonomy. The identity of the social connections might be dissolved suddenly and cheaply. Whereas the autonomy of a second-order coupling is easily maintained while the system is alive, the autonomy of a third-order coupling is never accomplished. As a consequence, this approach to social interaction describes the fact that each phase of coordination is a construction.

***Top-down versus bottom-up*.** Social systems that are autonomous in their collective behaviour appear and disappear in the course of the arrangement of individual activities. Two directions flows are necessary to maintain the autonomy of the social coupling. First, at each moment, individuals construct the social encounter to give rise to a collective activity. Second, this collective activity affects the encounters by giving new sources of disturbances. This double flow considers that all coordination has an autonomous *effectiveness* produced in real time in the co-regulation which does not belonging to any of the agents (bottom-up causality) and confronting to the activity of each agent (top-down causality).

Sense-makers interacting

Interaction processes are how social agents coordinate their sense-making during interaction which is how the meanings that individuals build on their activities correspond to the meanings simultaneously built by co-performers. Interaction processes are also how this participation in sense-making is experienced. Interpersonal coordination depends primarily on participatory sense-making.

Participatory sense-making. Building from the idea of autonomy and sense-making of a single agent, participatory sense-making is these concepts applied to the interaction process that appears when at least two agents have to coordinate their behaviour. In this case, the coupling emerges as autonomous even if the agents remain autonomous. This situation is typically defined as an interaction. From this step, each agent is part of the meaning world of the other, and finally they are coupled. The combination of two forms of sense-making is what is called *participatory sense-making*. In detail, participatory sense-making refers to co-construction of sense-making during an interaction. Agents coordinate their behaviour by sharing the meaning of the situation. This coordination depends on individual sense-making and on the connections between the interactors. In other words, agents have to understand each other, and this understanding includes the same meaning of the world. Thus, between the interactants, a convergence can be created which is not only physically observable but also relates to subjective experiences. This virtual convergence between the own worlds projected by each agent defines participatory sense-making. This participation in the construction of shared meanings appears when the individual processes of meaning assignment are affected such that a new domain of social meanings is generated that is not the sole property of either one of the two interactants.

ENACTION AND COLLECTIVE BEHAVIOURS

In sport science, collective behaviours have been investigated based on different theories. The first was an approach that referred to a form of *methodological individualism* (Theureau, 2003). Methodological individualism focuses on describing and studying the individual characteristics of the actors within an activity. By contrast, collective activity has been understood as an entity in its own right; it is then a question of essentially studying the collective without accounting for individual activity. This is qualified as *methodological collectivism* (Theureau, 2003). The enactive approach assumes the autonomy of the agent, because in these conditions it seems difficult to consider the collective without also being interested in the individual and without knowing the individual’s own world. Moreover, it seems not possible for enaction to fit into methodological collectivism.

Enactivism has been fruitful in showing how qualitative descriptions of sport activities offer a counterbalance to current behavioural theories (Poizat et al., 2013). In terms of teamwork investigation, the approach has been mobilised to analyse the joint action of rowers (R’Kiouak et al., 2017), basketball players (Bourbousson et al., 2012), and table tennis teammates (Poizat et al., 2009).

Dynamical system theory

> *For instance, when we observe a crowd of people walking on a busy road, the fact that they walk is not surprising, and we do not label this a case of coordination since walking is one of the things people do on a road (as opposed to, say, flying). But if we find that they are all walking in the same direction this could be a correlation, and if we suspect that this is not by accident, we can hypothesise the presence of a coordinating factor*. (De Jaegher & Di Paolo, 2007, p.490)

In order to put the interaction process at the centre, several authors have based the enactive approach to social interactions on the concepts of dynamic systems theory (De Jaegher & Di Paolo, 2007; Laroche et al., 2014). The fundamental connection between the autopoietic system and its environment assumed in the enactive approach, allows us to study human activity in the way the ecological approach (Gibson, 1979) or the dynamical approach have been used to study motor control (Kelso, 1995). In these approaches, interpersonal coordination is defined as a non-accidental correlation observed between the behaviours of two or more agents. In another words, it is the identification of a coherence that exceeds the probability observable by chance with regard to what these systems are capable of doing (De Jaegher & Di Paolo, 2007).

In sport science, team structure is assumed to emerge from the adjustments between the players and to exhibit signatures of a self-organised system. Understanding team behaviour is thus wed to the investigation of how real-time interactions between team members and opponents occur during the emergence of spatiotemporal conditions of play at different levels. In line with dynamical systems principles, metrics have been considered as *order parameters*, while significant local constraints as observable at a more microscopic level of description are designated *control parameters*. A control parameter is defined as a variable with the potential to modify the essentials of team behaviour (i.e., the order parameter), when the variable evolves beyond a critical value. Some researchers have adopted a prism that overlooks the way individual interactors in the system themselves manage their space-time interactions. However, when one considers humans are uncertain interactors not determined by external factors, being able to exhibit very distinct own worlds and to freely change their interaction modality, disregarding environmental, observable reason, a research gap remains in describing how individual interactors' perspectives matter in how team behaviour unfolds.

Definition of collective cognition

Active individual regulation refers to how individuals adapt their behaviours to make them suitable for collective needs when they are engaged in the spatiotemporal production of collective behaviour. The coherence that is created between the activities of construction of meanings and the behavioural patterns of interpersonal coordination is an articulation of the cognitive domains of several interacting agents (Bourbousson, 2015, De Jaegher & Di Paolo, 2007). This coherence cannot be related to the simple adjacency between physical phenomena and experiential phenomena but concretizes what collective cognition is. Teams are complex and dynamic systems, cognition is a collective activity indexed to a context, the interactions between the members are the collective cognition, and collective cognition is a multi-level phenomenon. Collective cognition is also dynamic and need to be constructed at each time of the collective behaviour elaboration.

ENACTIVE APPROACH AND HUMAN PHENOMENOLOGY

> *Bodily life-regulation is constitutive part of phenomenal consciousness*. (Shapiro, 2014).

The enactive approach is inspired by phenomenology, which comes from the philosophical investigation of the experience and consciousness of the individual. The focus on explaining how participants regulate their ongoing activity and contribute to collective behaviour is necessarily associated with the description of the phenomenon of self-consciousness. More generally, the enactive approach allows us to describe the role played by the phenomenon of consciousness among the agents engaged in a collective activity. More particularly, it allows us to understand the capacity of the agents to share experiences and to understand each other. In the case in which agents actively regulate their behaviour to each other, the own worlds of at least two agents are co-determined, which means that each agent stimulates the other’s areas of disturbance. The regulation of human action in the world is shaped by phenomena of consciousness and the *sense-making* of an agent is in the process of experimentation. Phenomenology allows researchers to analyse data from perspectives other than those that have been traditionally implemented, and the analysis switches from a third-person perspective to a first-person perspective (Petitmengin, 2006).

From the third-person perspective to the first-person. Initially, this phenomenological approach allows us to remove two pitfalls that the third-person point of view cannot avoid. Indeed, the interactions cannot be fully observable from the outside point of view and it also seems difficult from the outside point of view to ensure the relevance of the description of the internal organisation of an act.

Considering this, methodological objections can no longer occur (Vermersch, 1999). Insofar as a certain object of research does not concern itself specifically with the field of the unconscious, then the third-person point of view cannot be the only valid point of view. The assumption that agents are users of their own cognition and that she is the only discriminator of her own world can be approached only through what the subject may come out of and is, therefore, inevitably a point of view in first person (Vermersch, 1999). De Jaegher and Di Paolo (2014) emphasize the conscious perspective. However, cognition contains a pre-reflexive consciousness and therefore relatively transparent to the person who implements it. To study the own world, it is necessary to invest the lived experience of the agent. It is necessary to understand in which world agent is immersed to understand what agent lived. The phenomenology approach considers that one can understand the essence of things with the consciousness. Verbalization in the first person is a long and difficult job that requires learning to stabilize the usually capricious attention (Petitmangin, 2006). The first-person perspective contributes to the relevance of the theory of enaction. If the phenomenological approach argued the idea that the cognition could be understood based on the consciousness, it is because of the pre-reflexive self-consciousness.

Pre-reflective self-consciousness

Pre-reflective self-consciousness reveals people's capacity to account for their own activity and to grasp the reality in which they are immersed. The hypothesis of pre-reflexive consciousness insists on the fact that a human agent can at any moment, by means of the meeting of favourable conditions, show, mimic, simulate, tell and comment on his or her activity to another person. The pre-reflexive consciousness through interviews (e.g., self-confrontation) is the theoretical element that allows to describe the subjectivity of the agent.

Even if the theoretical concept is clear, it seems necessary to justify the possibility of obtaining the self-consciousness from a scientific and methodological point of view.

Collecting experiences from pre-reflective self-consciousness

If we consider access to the phenomenological level as necessary to understanding structural coupling (i.e., agent to environment), then it is involved the collection of data at a level of which the subject can be aware and that he or she knows how to express. Self-confrontation interview techniques refer to specific forms of phenomenological stimulated recall. Also called enactivist interviews (Rochat et al., 2017), self-confrontation is dedicated to facilitating the expression of participants' pre-reflective self-consciousness, as experienced during the real-world activity under study. This technique is consistent with the enactivist approach adopted in team sports (for scientific accounts obtained using this technique, see Bourbousson et al., 2012) and affords special attention to the implicit ways in which a given player experiences an ongoing activity. It illustrates the state that individual activity reveals autonomous characteristics that are not reducible to behavioural descriptions (Maturana & Varela, 1980).

Scientific Contributions

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Chapter 2: Scientific gaps
Chapter 3: Epistemology
Chapter 4: Rational
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Chapter 4 - Scientific orientation to bridge the gaps

This chapter aims to present the scientific orientation which allows us to bridge the gaps. To clarify, three main gaps have been detected: (1) the active regulation of the individual is mostly presupposed rather than empirically investigated, (2) the link between individual activities and the correlate pattern in the collective behaviour is not reported in the literature, and (3) there is a need to delineate and control the individual regulation. We suggest a scientific approach to bridging these gaps. The first aim of this dissertation is to empirically investigate the informational resources supporting individual activity. With the help of an enactive approach, we attempt to fill the first gap. However, the enactive approach, by considering the own world of humans, does not afford the possibility of investigating the consequences of the type of regulation at the level of collective behaviour. The second aim of this dissertation is to test hypotheses about the individual regulation modality and observe the consequences in collective behaviour. A model simulates collective behaviour based on different individual regulation modalities. Therefore, the individual collective behaviour was characterised by computed collective metrics. However, with simulation the regulation is determined by the researcher, it seems interesting to test the possibility to control the individual regulation in a natural setting in way to determine the regulation also in natural setting. The third aim was to delineate the regulation and examine the possibility of controlling individual regulation. With the help of an experimental design, we create interactive rules that could imply a certain type of regulation.

Chapter overview. To construct a powerful and well-argued rational, we explain how to bridge the gaps with design ideas, with theoretical concepts and methods. An argument is presented step-by-step for how to bridge all of the gaps.

Investigating informational resources

Scientific design. The aim of this study is to investigate the informational resources supporting individual activity. The design of the study takes into consideration the fact that research describing this kind of spatiotemporal information is scarce. While isolated studies have provided evidence of a spectrum of informational resources (i.e., categorised as local and global), the nature of such resources has been mainly theoretically presupposed rather than empirically described (Bourbousson & Fortes-Bourbousson, 2016). The study aims to describe a broader spectrum of spatiotemporal attunement possibilities and how such possibilities would occur together in a complex naturalistic setting. Therefore, this exploratory study provides a deeper understanding of how team members are dynamically attuned to the team coordination needs of their joint effort in real time.

The need for qualitative analysis. Our hypothesis at this stage involves studying a large number of members in the collective rather than the dyads often considered in the small theoretical sketches constructed to conceptualize social couplings (e.g., De Jaegher & Di Paolo, 2007). To investigate all the informational resources from all the members of the group, we need to conduct self-confrontation interviews. A thematic analysis applied to the collected data will allow us to bridge this gap.

INDIVIDUAL ADJUSTMENT CHANGES AND CORRELATES IN COLLECTIVE BEHAVIOUR

Scientific Design. To test the hypothesis about individual regulation and its correlates at the level of team behaviour, two options are appropriate. Indeed, a first possibility could imply a mix of phenomenological and behavioural data (R'Kiouak et al., 2016; Seifert, Adé, Saury, Bourbousson, & Thouvarecq 2016). For example, based on a phenomenology of the individual level, it might be possible to describe the correlate spatiotemporal behaviour that appears at the same time. However, this method would not allow a generalisation of the result due to the complexity of analysing subjective and objective data from the same time point in ecological situations. Building on this idea, we could create a model that would control individual regulation and would afford the possibility of testing various types of regulation without being constrained by the need to subjective data. Therefore, the possibility of simulating significant collective behaviour would increase the power of the generalisation of the result. To study the correlates in collective behaviour, it is necessary to control all parameters. In this sense, creating a simulation model could help to bridge the gap.

The need for simulation. In order to test the effects of different adjustment modalities, our project needed a simulation model of the space-time collective behaviour of a multi-agent system (MAS). This MAS has been built to reflect the essentials of football teams' behaviours, considered complex social systems. We expected to show how the dynamical patterns of collective behaviour depended on adaptive adjustment modalities implemented in the behaviours of the individual agents composing the MAS. We constructed a football model that exhibits teams' collective behaviour that was in line with a real football team's behaviour, which led us to consider our model realistic in terms of the space-time view.

DELINEATING AND CONTROLLING THE INDIVIDUAL REGULATION

Scientific design. In the simulation model, individual regulation was implemented based on the subjective data collected in the first study. Moreover, the second study showed specific collective patterns arising from the diversity of regulation. In another study, it could be interesting to investigate the capability for controlling individual regulation in a natural setting in a way to produce expected collective behaviour. The first gap is focused on informational resources, whereas the second is focused on adjustments. It seems interesting to delineate regulation by understanding the link between informational resources and adjustment. In other words, a local informational resource does not necessarily involve a local adjustment.

The need for experimental design. An experimental design would allow us to investigate the possibility of controlling individual regulation. Indeed, by giving different interaction rules to participants in various situations and therefore conducting a qualitative analysis of participants' regulation, we would generate results that would contribute to the understanding of individual regulation control. Also, if the ultimate goal is to have opportunities to discuss our results with more varied fields of research, the construction of an experimental paradigm for studying collective behaviours and their modes of regulation remains a path to explore.

CHAPTER 5 - GENERAL METHODOLOGY

In the previous chapter, we presented the scientific orientation, identified the gaps to be bridged and outlined the objectives of the research project. To achieve these objectives requires a strong methodological approach and design. The complex and varied methods developed for the project are presented in this chapter.

The first objective was to investigate the informational resources supporting individual activity. The theoretical concept established by the enactive approach pointed to the need for phenomenological data. The methods section offers explanations about how to collect and analyse subjective data. The second objective was to provide insight into how changes in players' individual adjustments give rise to distinct correlates in terms of simultaneous team behaviour. A simulation study of football contributes to this aim. To understand the correlate collective patterns, we constructed a model based on the subjective data obtained in pursuing the first objective. The collective patterns were studied based on established metrics. The final study is based on the same methodological approach as the first one.

In brief, the complex method developed for this research project can be described in three parts: (1) the collection and treatment of subjective data, (2) the elaboration of a simulation model based on subjective data and (3) the use of metrics to characterize the simulated collective patterns.

***Chapter overview*.** This chapter has been written in such a way as to not only describe the project methods but also provide guidance for future experiments. For this reason, the elaboration of this chapter does not include the data from this project. For further information about the specific project data, see Chapter 6 and appendices.

PHENOMENOLOGICAL DATA ANALYSIS

The collection and treatment of phenomenological data are scientifically valid from a theoretical perspective. The major theoretical points were discussed in Chapter 2; this chapter focuses on describing the data collection and treatment associated with the project.

Data collection

Video recording. Collected behavioural data serve two objectives. These data help in building a behavioural account of the game, but they also support interviews that are used to collect verbal data. The collection of video data is made by camera or drone. The calibration of the camera should be carefully adjusted, based on the researchers' experiences working in team sports, to facilitate the self-confrontation interviews that are conducted afterwards. In particular, the camera viewpoint helps participants re-experience their situation and describe their activity. Thus, the camera should be placed as a TV camera would be placed, because individuals are used to seeing recordings from this point of view. A wide-angle camera could support continuous capture of all movements of the participants.

Selected sequence. From the overall video recordings, the researcher has to select a sequence that corresponds to the aims of the study. For instance, if the researcher focuses on the attack, all attack sequences should be selected. In the case in which the research aim does not directly suggest an appropriate sequence, the researcher could ask an expert for advice. For example, if the research is meant to describe the collective performance, which is not totally objective, the researcher could turn to the coach, asking for an example of a sequence when players are deeply involved in a joint task. The coach would select a sequence immediately after the game to delineate an excerpt illustrating teamwork quality. The researcher would then have to review this choice, confirming the presence of numerous salient events (e.g., corner kick, off side, direct free kick, or yellow card) and also considering opportunities for helping players to remember their game and provide detailed comments in response to a sequence. Finally, the choice of the sequence could be confirmed by the players' reporting a satisfying team performance (e.g., a feeling of togetherness, every player involved in the collective behaviour principles).

Interview constraints. The verbal data are collected from individual postgame interviews with each of the participants (Fig. 4). The first rule is to conduct the self-confrontation interview (or other type of interview) as soon as possible after the video recording; within 48 hours is required. During the interviews, each participant should watch the selected video sequences with the researcher. The recording should be stopped, by either the researcher or the participant, according to the needs of the research goal or the necessity for the participant to talk. Basically, specific action in the video is scrutinised during the interview.

Self-confrontation interviews. All interviews are recorded using a video camera and an audio recorder. The participant has to describe and comment with details, relating the dynamics of the lived experience at each point. The researcher should try to help the participant to *re-experience his or her game*. The interrogations of the researcher should be about what happened for the participant at each instant and what the participant, felt, thought and perceived, according to the needs of the study. The interview questions should not be directly addressed to the nature of the study objective but should preserve as well as possible options for open expression of the participants' lived experiences. For this reason, yes-or-no questions must be avoided. Importantly, participant activities under study should essentially be driven by the situational understanding of participant. Participants should not discuss the future or their expectations about what they may have to do. In other words, it seems necessary to consider all methodological precautions (Trudel, Haughian, & Gilbert,

1996) that exist to prevent participants from making inferences or generalising about their thinking (Theureau, 2003).

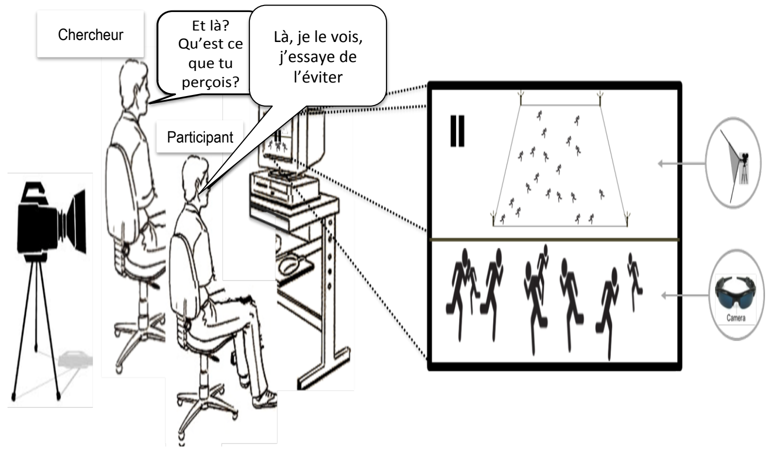

Figure 4. Illustration of the self-confrontation interview conducted to record the subjective data associated with the subjectivity of each participant.

Saturation. Participants are all interviewed from the same question sequence. The sequence has to last long enough to reach a saturation level. Saturation is defined as the point at which all of the responses have been made, which means adding participants or time to the sequence will not help to extend data quality. Previous research has suggested numbers of participants and sequence duration as representative samples that are sufficient for reaching data saturation (Bourbousson, Poizat, Saury, & Sève, 2011; Bourbousson, Poizat, Saury, & Sève, 2012). 10 minutes could be considered an appropriate sample for qualitative analysis of the verbal dataset.

Data analysis

In qualitative research, several methods have been developed to treat the data. We present here the thematic analysis (Braun & Clarke, 2006; Braun et al., 2016).

Behavioural description. Using the video and based on the selected sequence, we carried out a comprehensive behavioural description. This step consisted of noting the ball carrier at each moment in time, players' positions near the ball, and the spaces that were particularly dense in terms of players and those that were relatively free. Other observable football-related events were reported when salient (e.g., defensive errors and stealing the ball).

Transcription. Verbal data obtained during self-confrontation interviews should be fully transcribed to obtain a verbatim. This transcription should include a record of details as they unfold during the interview. For example, it is necessary to note the salient observable behaviour of the participant during the interview in terms of breaks and hesitations. It is also necessary to check the tapes to verify that there is no incompatibility between what the participant says and what the video shows (Braun et al., 2016). Before beginning the analysis of the data, there is a need for a deep familiarisation (Braun et al., 2016) with the data and it is crucial to read and annotate the transcript several times. The analysis of the data requires several steps.

The first two steps are specific to an activity-centred framework (Fig. 5). The following steps focus on the principles of thematic analysis (Braun & Clarke, 2006): (1) accounting for the way participants reported their experience of the game dynamics, (2) delineating meaningful units of activity (MUAs) as identifiable within each participant's experience report, (3) coding the investigating contents supporting each MUA, and (4) developing themes by clustering investigating contents.

Steps 2 and 3 should be conducted by two researchers on a data sample selected for critical dialogue. Once these researchers have dealt with the content of meaningful units of activity and how they should be identified, the remaining data can be analysed by a single author. There is more explanation about the epistemological conditions of such a procedure in the article by Smith and McGannon (2017). Step 4 could be performed by a single author, but it is said that challenging the analysis with other authors at each iteration benefits the quality of the research (Smith & McGannon, 2017).

Considering that a researcher cannot build theory-free knowledge, the method exposed here reflects an inductive processing. Whatever the topic of the research, the aim is always to obtain an exploration of content supporting the activity of the participant which is interesting and, as much as possible, data-driven.

Accounting of the way participants reported their experience. Based on the transcript data, this step aims to characterise how the participants experienced each moment of the game that was personally lived. First, the way participants dynamically experienced the game is reconstructed by synchronising in time the behavioural description of the game with the related portions of the verbal transcripts of each participant. From this procedure, a timeline of verbalisations is obtained that are assumed to be expressions of the way in which the activity was experienced by each participant. As the behavioural description was common to all participants, this procedure provides a synchronisation of participants' overall verbal data.

Delineating meaningful units of activity (MUAs). Based on the timeline of verbalisations obtained, this step consisted of recognising the data relating to the study aim while identifying how such data were related to one or more discrete meaningful units of experience. In this light, only the portion of participants' activities relating to how they contributed to creating, maintaining, or changing a part or all of the ongoing spatiotemporal collective behaviour was first retained. Within such portions, discrete MUAs were identified. An MUA was considered to exist when it formed a consistent unit from the viewpoint of the given participant, not in terms of the ideas expressed by the participant in his or her verbal report but in terms of the action performed that the participant was commenting on.

Each MUA thus reflected an instant of activity, and this activity was related to regulating collective behaviour. An MUA started with the participant experiencing a new setting and ended with the beginning of a newer one. MUAs lasted around two seconds on average. During the sequence under study, the number of MUAs are identified across all participants.

Time	Time Code	Behavioural Description	Verbatim's Extract	MUA (n)
5′27″	60	- The team is in attack phase. - The ball-carrier M6 is in the middle of the field. - M6 is not on a time pressure. - M6 easily moves forward with the ball.	Researcher: Now he [one of his midfielder, M6] receives the ball… what is important to you now? D3: *“You know at this time, I'm still waiting, I see that our team is quite forward on the field, thus I decide to stay in my place and follow the movement.”* Researcher: What do you mean by movement? D3: *“Actually, we move forward together.”*	The player is aware of the team's positioning and collective forward movement (170)
6′22″	73	- There is a long pass for the opponent attacker. - Two partners in defence (D1, D2) are moving to the opponent ball carrier. - The teammate goalkeeper is talking. - It is potentially goal action.	Researcher: Here in this situation [there is a long pass for the opponent attacker] what are you thinking at this time? M7: *“I think I will come back, actually I'm focus on the ball and tried to get closer to the ball, even if I'm not really important here I stay focus on the ball because if one of my defender catch the ball I need to be ready.*”	The player is focus on the ball, observing when the ball would be passed (46)
8′43″	95	- M5 receive the ball. -M5 is just behind the middle line of the field. - M5 is not on time pressure.	Researcher: You receive the ball… what is going on for you now? M5: *“Now when I receive the ball, I'm looking everything around, I keep the ball until to see the near situation is going to be better, at this moment I see no one is free for a pass.”*	The player is looking every event around, without being focused on a specific element (129)

Figure 5. Illustrations of the first two methodological steps in Feigean et al., (2018).

Coding the investigating contents supporting each MUA. The aim of this step is to determine the investigating content that supported each instant of activity delineated in the previous step (e.g., identifying the emotion within each MUA). First, the objective is to define the *investigating contents* on which the research is focused. For instance, the first study of this project focused on informational resources (i.e., investigating contents), and the informational resource was defined as ‘*the elements that are significant for a given team member at a specific moment and account for what informational resources the participant considers while acting*’(Feigean, R’Kiouak, Seiler, & Bourbousson, 2018, p. 159).

Contents are labelled so as to preserve their complexity, especially when composed of many pieces of information from the same part of the transcript. This step gave rise to a specific *number of contents*. The analysis was performed for each participant's chain of MUAs, and then synthesized across all participants to provide a general account. At this stage, each content was labelled in a manner that respected the singular experience that each participant had verbalised.

At least three rounds of coding are needed to refine the existing codes, ensuring the homogeneity of the investigating components identification and formulation. While the coding procedure is considered mainly semantic (Braun & Clarke, 2006), some components are not totally commented on by the participant. This suggests that researchers have to infer from the transcript as content from a comprehensive analysis of the participant's lived experience by scrutinising the previous MUAs in addition to the behavioural description of the game events. However, even if inferences are acceptable, less than 5% of the total of the investigated contents identified required inferences by the researchers.

Developing themes through clustering investigating content. Finally, the investigating contents identified in the previous step are merged into related themes (Braun & Clarke, 2006). This process consists of searching for commonly recurring themes in all identified investigating content.

First-order. The first step rests in grouping the total amount of investigating content like the informational resources, for example, into categories. The first created category is called *first-order* themes. This step involves two criteria. First, first-order themes should be exhaustive. In other words, each investigating content must be included in one of first-order themes. Secondly, first-order themes should be exclusive. This implies that their labelling and their content-related definitions must be sufficiently discriminating in a way that no investigating content could fit with two first-order themes. Overlapping themes should be avoided. Each time a new investigating content is processed to further delineate first-order themes, the previous temporary themes should be changed and rearranged. This step gives rise to new themes and allows removal of old themes. During this procedure, the goal is to develop themes that are internally coherent, consistent, and distinctive (Braun & Clarke, 2006).

Naming. This step also includes naming the themes so that each wording retained does not change the underlying logics of the clustering, while still respecting the participants' singular phenomenology.

Saturation. Data saturation (Fusch & Ness, 2015) is obtained after processing a portion of the overall investigating contents. For example, in the first study, saturation was effective for six players (i.e., 378 singular informational resources), which means that no further rearrangement of first-order themes was required after this point, and the entirety of the remaining investigating content (i.e., informational resources) perfectly fit within the existing proposed themes. From this step, a certain number of first-order themes are identified.

Second-order. Due to the number of first-order themes identified, it seems necessary to execute a second round of thematic analysis applied to these first-order themes. This step is similar to the previous one and aimed at identifying higher-level patterns into which first-order themes could fall. From the number of first-order themes, a reduced number of second-order themes should be described. This second process is considered as a methodological step and it is basically not reported with the results in a paper.

Third-order. In the final round of thematic analysis, a reduced number of third-order themes are obtained. The obtained three levels of themes are considered relevant and it is recommended by Braun et al. (2016) to have a final three-level structure made of subthemes, themes, and overarching themes. Third-order themes are retained as the main and particular investigating content for discussion. In each round of thematic analysis, the initial singular investigating content are carefully checked. This step is essential to get final third-order themes that relate well to participants' real-world experiences of the situation. An analysis of the specific occurrences of each investigating content within each player's course of experience could be performed to enable the most prominent themes to be identified and also to show how such investigating content are observed in each of the participant's activities.

ELABORATION OF A SIMULATION MODEL BASED ON SUBJECTIVE DATA

As with the first part of the method chapter, it is important to mention that this section has been written as a guideline for future research. For this reason, this section includes descriptions of the mathematical equation that could be use in others projects. The aim here is to provide information about the methodological steps in the elaboration of a multi-agent simulation model. For further specific information about the model developed in the second study, see Chapter 6 and appendices**.**

An objective of the project was to provide insight into how changes in agents' individual adjustments give rise to distinct correlates in terms of simultaneous team behaviour. From a methodological aspect, to observe relationships between the individual regulation and collective behaviour levels requires control of all parameters and changes of the regulation parameter. In an ecological situation, control of all parameters is impractical, and thus there is never a certitude in explaining a direct relation between micro and macro levels of analysis. For this reason, elaborating a simulation model seemed to be a satisfactory choice for studying the interdependence between the individual adjustment and the resulting collective patterns.

The specificity of this model is that the social forces are based on the subjective data provided by the results from the first study. For the sake of simplicity, the individual regulation computed is reduced to the local and global regulation.

Foundation of a multi-agent system. A multi-agent system (MAS) is a system composed of a set of agents (e.g., processes, robots, or humans) located in a certain environment and interacting according to certain relationships. An agent is an entity characterized by being at least partially autonomous. According to this, the elaboration of an MAS should start by determining the abilities of the autonomous system and the geometry of the environment in which agents move. Second, it is fundamental to define the environmental constraints that are applied to agents. Last but not least, it is necessary to decide how the agents will interact (i.e., social interaction rules or adjustments).

In sport science, a model of collective football behaviour should be characterised by constraints (1) related to the specific environment, which can be the limitations of the field, for example; (2) related to the agents' adjustment, which illustrate how they interact together to perform as a team; and (3) related to the specific sport rules – as for a pass, for example. In other words, agents feel constraints of two different sorts: (1) the physical forces, in which are included the avoidance of physical contact but also any relation with the environment and (2) the social forces, which consider the agents' interpersonal coordination or their willingness to perform as a football team.

Autonomous agent. The model computed assumes that pedestrians are active mechanical objects: their behaviours can be described by the classical Newtonian laws and by forces. Their motions appear due to a desired velocity v_d that each individual aims to achieve. Thus, agents are propelled by a force which depends on v_d. On the other hand, friction limits their velocity, and the balance of these two terms acts as a saturation term. We wrote this using Stokes' friction law because it is the simplest approach. The model also computes the mental process through a Langevin-type equation where there are external influences or forces, an inner latency with a time τ_d, a mental inertia m_m and a Gaussian noise η which models stress or confusion with an effective diffusion coefficient D. The resulting equations are:

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \sum \mathbf{F}_{\text{physical}} + \frac{m}{\tau}(\mathbf{v_d} - \mathbf{v})$$, (1)

and

$$m_m\frac{\mathrm{d}\mathbf{v_d}}{\mathrm{d}t} = \sum \mathbf{F}_{\text{social}} - \frac{m_m}{\tau_d}\mathbf{v_d} + \frac{m_m}{\tau_d}\sqrt{\frac{2D}{\tau_d}}\eta$$. (2)

Geometry of the environment. Agents move on a field of width ℓ_x and length ℓ_y. The coordinates axes are called x and y, as usual. Vectors are indicated with bold arrows. So, the unitary axes vectors are e_x and e_y. Positions are generally called r, and agents are labelled by an integer i. The origin of the frame is fixed at the centre of the pitch (Fig. 6).

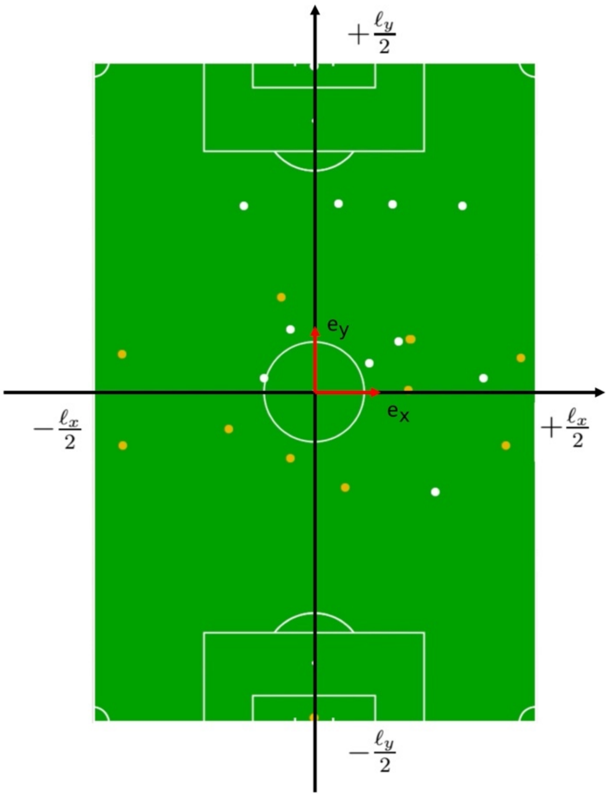

Figure 6.. Example of the geometry of a simulated environment. Football pitch is computed with a centre of field (0;0) and with width ℓ_x and length ℓ_y.

Environmental constraints - Physical forces

The term *physical* forces describe the fact that each agent is constrained by environmental rules without any delay resulting from mental processes. In the model, two forces are considered as physical: the collision force and the side force.

Collision. First, collision force F_C forbids two agents *i* and *j* to be at the same location (*x;y*). This force describes the spatial occupation of a single agent, and the avoidance radius r_c is the width of the agent. Its potential diverges when the distance between the two agents vanishes, so the force is as follows:

$$\mathbf{F_C}(\mathbf{r}) = \begin{cases} 2U_c\left(\frac{r_c}{r^2}\right)^2 \mathbf{r}, & \text{if } r < r_0 \\ 0, & \text{anywhere else,} \end{cases} \quad (3)$$

where $r = r_i - r_j$, with r_i as the position of agent *i*, U_c as the norm of the potential and r_c as the core-radius of an agent. In our model, the collision force is considered only when the distance of two agents is less than a parameter r_0.

Side. Second, the side force is constant and equal to F_B when an agent moves off of the field, and it vanishes elsewhere. The side force describes the way the agents try to stay in the pitch or the way they try to come back on the field:

$$\mathbf{F_B}(x_i, y_i) = \begin{cases} F_B \mathbf{e}_x, \text{ when } x_i < \frac{-\ell_x}{2} \\ -F_B \mathbf{e}_x, \text{ when } \quad x_i > \frac{\ell_x}{2} \\ F_B \mathbf{e}_y, \text{ when } y_i < \frac{-\ell_y}{2} \\ -F_B \mathbf{e}_y, \text{ when } y_i > \frac{-\ell_x}{2} \end{cases}, (4)$$

where ℓ_x and ℓ_y are the dimensions of the field.

At this stage, the simulated agents are able to move on the delimited area; agents are computed to stay on the field and avoid the contact with the others. Observations of the simulation do not provide any similarity to a football game.

Social constraints - Social Forces

The study aimed to compare two types of interaction between agents. In this section these two types of interactions are described in term of equations. These interactions were considered as social forces and called *local* and *global* adjustment.

Local. Local adjustment force F_L occurs when an agent *i* adjusts it behaviour by keeping a distance d_p from a specific team member *j*. The given team member is chosen as the nearest partner agent *i* in the cone centred on *i*, with a half-angle $\frac{\pi}{3}$ and with an axis pointed at the ball. A symetric attractive potential, whose well is around d_p and for which the well width is approximately δ, can be written as follows:

$$U = U_L \frac{-1}{\left(\frac{d_{ij} - d_p}{\delta}\right)^{2\alpha} + 1}. (5)$$

The derived force is then:

$$\mathbf{F_L} = U_L \frac{2\alpha}{\delta} \frac{\left(\frac{d_{ij} - d_p}{\delta}\right)^{2\alpha - 1}}{\left(\left(\frac{d_{ij} - d_p}{\delta}\right)^{2\alpha} + 1\right)^2} \mathbf{e_{ij}}, .(6)$$

where d_{ij} is the direction from *i* to *j*.

Global. Global adjustmnt force F_G occurs when an agent *i* adjusts it behaviour by taking into account all other agents *j*, which includes both team members and opponents. The agent *i* tries to move in order to maximise the covered surface on the pitch. The position of each agent is defined as the centre of repulsive potential. This potential is anisotropic and regular when the distance between agents vanishes. Our aim is to avoid numerical instabilities induced by divergence. Also, the collision force already prevents the distance between agents being reduced to 0. The total potential, which is the sum over every agent, is stated as follows:

$$U = U_G \sum_{j=1, j\neq i}^{n} \frac{g_j}{\left(\frac{d_{ij}}{\delta}\right)^{2\alpha} + 1}, \quad (7)$$

where n is the total number of agents, d_{ij} is the distance between agents i and j, δ is the size of the repulsive zone, α is a coefficient giving the verticality of the potential, and g_j is a coefficient that allows for weighting the importance of opponents compared to team members.

The derived force is

$$\mathbf{F_G} = -U_G \frac{2\alpha}{\delta} \sum_{j=1, j\neq i}^{n} \frac{\left(\frac{d_{ij}}{\delta}\right)^{2\alpha-1}}{\left(\left(\frac{d_{ij}}{\delta}\right)^{2\alpha} + 1\right)^2} \mathbf{e_{ij}}. \quad (8)$$

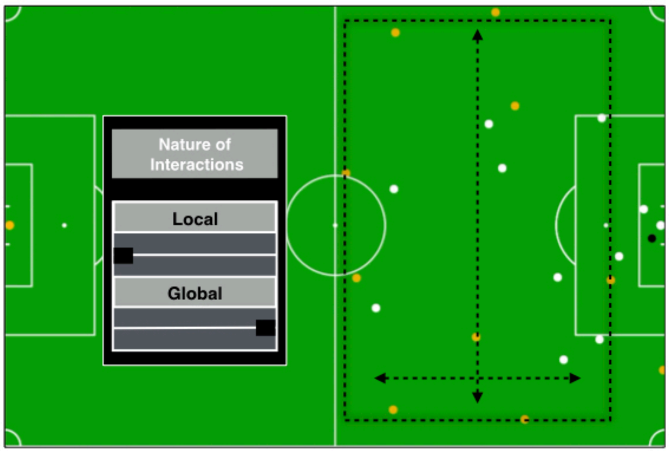

Figure 7. Example of the set-up of the social interactions in the simulated model.

At this stage, the simulated agents are able to move based on the physical rules but also to interact with each other according to the adjustment modality setting, which is either a local or a global adjustment modality (Fig. 7). The observations of the simulation do not off any similarity to a football game. To model observable football games, equations about rules in football have to first be computed.

Specific rules in football

This section explains how football rules are implemented in the model. We have chosen to describe the way the ball is managed in order to get more realistic behaviours, including the pass and the catching. Also, the following section defines the way agents are initialised in a common team line-up (e.g., how many agents are defenders) and how agents move based on the situation. Finally, specific knowledge about football is computed, such as the movement of the ball carrier, the behaviour of the nearest defender and the offside.

Pass. The ball carrier has a certain probability *P* of passing the ball. This probability increases when an opponent is near to the ball carrier. The pressure of the opponent is perceived from a distance D_p and decreases linearly with the distance to the defender:

$$P = max\left(\frac{dt}{T_p}, 1 - \frac{d_{ij}}{D_p}\right), \quad (9)$$

where d_t is the time step, T_p is the mean time of pass without pressure from any opponent and d_{ij} is the distance between the ball carrier and the nearest defender.

To find a teammate to exchange the ball with, the agent checks for the nearest teammate in the direction of the goal. For this purpose, angles α_i are measured to the team members *i*. The angular origin is taken as the direction from the ball carrier to the goal, and so it is a dynamic variable. Then absolute values of angles α_i are ranked from the smallest to the greatest. On the other hand, the risk of being intercepted by an opponent decreases with the opponent's distance from the ball carrier r_j. Thus, opponents are ranked according to their distance from the ball carrier, nearest to farthest. From the first team member in terms of ranked angle measures to the last one, the model checks to determine whether one is able to receive the ball without interception by an opponent. First, to simplify our model, we assume that the pass velocity v_b is constant. Therefore, the speed v_b and the maximal displacement velocity of an agent v_0 define a certain angle α_0, with $v_0 < v_b$. If the future ball carrier is on the axis of the cone of half-angle α_0, and if this cone is empty of opponents, then the pass should arrive safely. Having just defined a cone of interception for the future ball carrier, a new cone of interception for an opponent can also be defined. Consideration of all of these cones partitions the space into forbidden zones. The algorithm for finding a pass direction consists of building this partitioning and then identifying the remaining spaces where the ball can move without being caught by an opponent (Fig. 8).

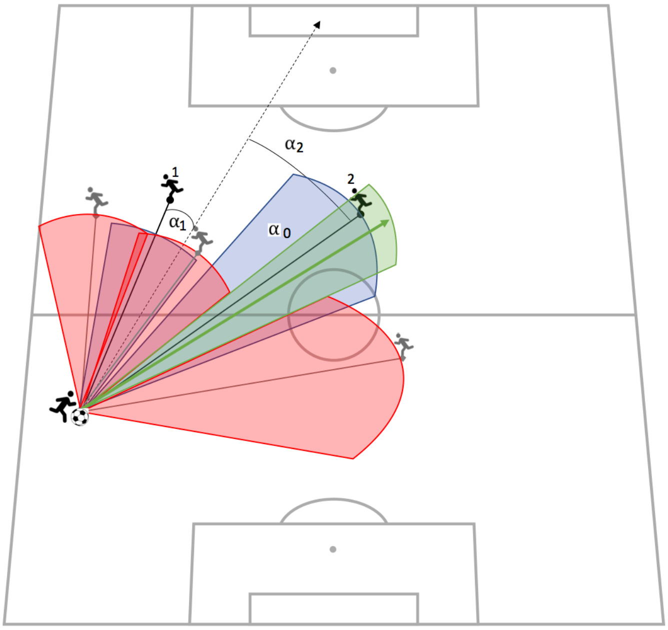

Figure 8. Steps to pass the ball: Rank the team members from α1 to αx. Rank the opponents by their distance from the ball. Provide a cone for each agent with α0 as angle, blue cone for team members and red cone for opponents. Seek for an available agent from α1 by looking for a green cone.

Catching the ball. Catching the ball is realised by the agent nearest to the ball on each team. The trajectory of the ball is along a line and moves with a constant speed v_b. The agent can move in any direction from the initial position r_j. So, to find the position of interception *r*, one has to solve

$$\begin{cases} \mathbf{r} = \mathbf{r_b} + \mathbf{v_b}\Delta t \\ (\mathbf{r} - \mathbf{r_j})^2 = (\mathbf{v_j}\Delta t)^2 \end{cases}, (10)$$

where Δt is the time parameter. The only new assumption is that this neglects the acceleration of the agent in making the jump between r_j and r if $0 < \Delta t < dt$, *dt* being the time step. In the case of this last event, or if the ball is free, then the ball becomes kept by a new carrier. If the ball is carried there is a given probability that the carrier will be *tackled* by an opponent.

Zone force. The zone force considers the individual area of each agent according to their position on the field (e.g., defender, striker, midfielder). This force is derived from a harmonic potential with a centre r_{zi} depending on the position of agent *i* on a specific team. In this way, an agent has a reference position on the field determined by the collective tactic (e.g., 4-4-2). Furthermore, one expects that the motion of the agent around r_{zi} can be anisotropic: for instance, the winger moves along the touchline. So, for each agent there is a preferred zone through a centre r_{zi} and two lengths λ_{xi} and λ_{yi} which define the extents of the zone:

$$\mathbf{F_Z}(\mathbf{r_i}) = -2U_Z\left(\left(\frac{x_i - x_{zi}}{\lambda_{xi}}\right)\mathbf{e}_x - \left(\frac{y_i - y_{zi}}{\lambda_{yi}}\right)\mathbf{e}_y\right). \quad (11)$$

To allow for consideration of continuous regulation of all the agents to the ball, the centre of the zone is not fixed but changes over the time according to the trajectory of the ball. According to the length of the field, the centre of the zone is calculated by adding a term to the agent position at the hyperbolic tangent of the ball position. The hyperbolic tangent function was selected to give a linear behaviour during the transition phase as the ball moves from one part of the field to another, and also so as not to create movement when the ball is near to a goal. This illustrates the offensive and defensive phases, in which agents are in part of the field, and the transition between these phases when the agents are moving from one part to the other. During the defensive phase, the horizontal movement of the zone centre is proportional to the movement of the ball which corresponds to the way a team shifts when the ball moves from one wing to another. In the offensive phase, the x of the centre zone does not depend on the ball position. A default value is simply multiplied by a coefficient η higher than 1 to spread the team around the ball.

$$\text{Offensive team}: \begin{cases} x_z = \eta \cdot x_{z0} \\ y_z = y_{z0} + \frac{\ell_y}{2}\tanh\left(\frac{2y_b}{\mu}\right) \end{cases}, \quad (12)$$

$$\text{Defensive team}: \begin{cases} x_z = x_{z0} + \frac{1}{2}x_b \\ y_z = y_{z0} + \frac{\ell_y}{2}\tanh\left(\frac{2y_b}{\mu}\right), \end{cases}, \quad (13)$$

where x_{z0} and y_{z0} are the default coordinates of the zone centre, ℓ_y is the length of the field, x_b and y_b are the coordinates of the ball and μ is the distance from which trajectories are linear.

Game situations. When a team gets the ball, the ball carrier is constrained to move toward the opposite goal, so we introduce a force to the goal:

$$\mathbf{F_{goal}}(\mathbf{r_i}) = \beta \cdot \frac{m}{\tau} \cdot v_0 \cdot \mathbf{e_b}(\mathbf{r_i}), \quad (14)$$

where β is a coefficient to modulate the intensity of the force, and $e_b(r_i)$ is the unitary vector pointing toward the goal from the agent location r_i.

For the nearest defender to the ball, at each time step, two cases can be encountered: either the ball is carried or the ball is free. When the ball is free, a force constrains the defender to move toward the interception point. If there exists a solution of equation (10), and if $\Delta t \geq dt$, then the agent tends to go to the ball under the action of a constant force:

$$\mathbf{F_{ball}} = F_{ball}\mathbf{e_b}, \quad (15)$$

where F_{ball} is a parameter, and e_b is the unitary vector from the agent to the ball. Second, if the ball is carried, the nearest defender is forced to go toward the ball carrier. Moreover, to be close as possible to the reality, the model also includes the off-side. The equation constrains the ball carrier to not pass the ball to a partner when he is off-side.

Summary of the simulation

Model. Twenty agents distributed in two entities were simulated in a continuous two-dimensional area, which is the pitch. The origin of the two-dimensional area was the centre of the pitch (0;0), and the length was initialized at 120 meters and the width at 80 meters. The time was partitioned into discrete time steps *t* with a regular scale. In this model, *t* was set to 0.05 second. Each agent was considered as an object constrained by different forces. This model was based on physical forces and social forces. First, physical forces illustrating the dynamics of agents and calculated according to each agent's respective coordinates (*x*;*y*) and velocity were the avoidance force, the zone force and the side force. Second, the social forces were defined as the local force or the global force (Fig. 9). The model simulated the behaviour of agents in naturalistic sport situations and used an integrative method to calculate the trajectories of the agents. The calculation process started with an initialization of the positions of the agents. Then, at each time step, forces applying to the agents were calculated. Finally, the acceleration, then the velocity, then the positions were reduced. Several processes were also involved and implicitly calculated during each case, for instance, side-out and off-side.

The model considered a desired velocity v_d integrated in the social forces' establishment. This velocity was related to the level of desire with which an agent wishes to move in considering the environment. It considered a characteristic time of decision making τ_d, corresponding to the response latency of the football agent, accompanied by a hypothetical mental inertia described by a mass m_m (i.e., 80 *kg*) in fundamental principle of the dynamics.

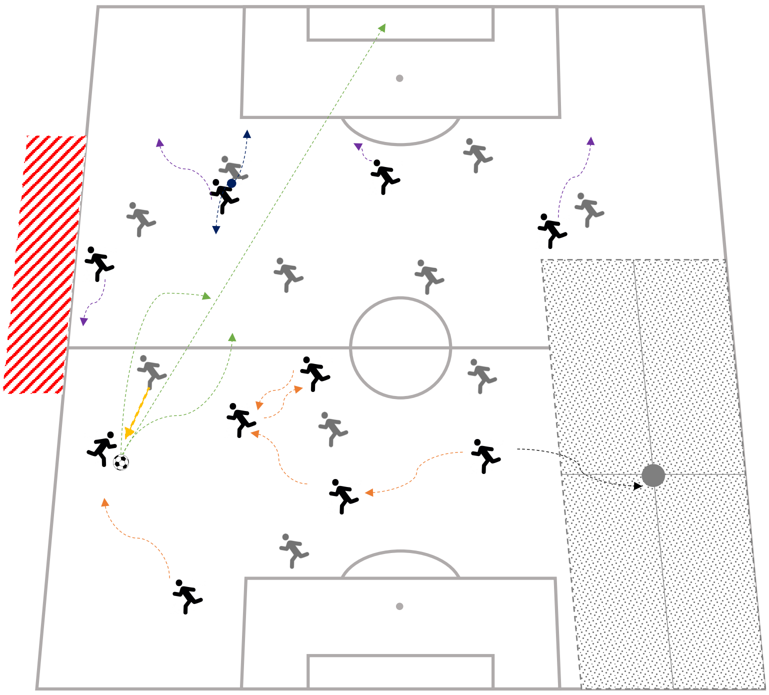

Figure 9. Illustration of the side force: Agents have to stay on the pitch (red hatched). Avoidance force: Agents avoid collision with other agents (blue arrow). Zone force: Agents are constrained by a specific zone (grey area and arrow). Ball carrier force: Agents have to go to the goal and avoid defenders (green arrow). Nearest defenders to the ball: Agents move to the ball carrier (yellow arrow). Purple arrows illustrate the global adjustment modality and the orange arrows illustrate the local adjustment modality.

Parameters. This model was simulated based on initial parameters (see Fig. 10).

Parameter	Symbol	Unit	Value explored
Closure distance	r_0	Meters	1 to 2
Time step	Δ_t	Seconds	0.05
Radius of agent	r_c	Meters	0.3
Velocity	v_0	Meters per second	3
Coefficient velocity limit	v_{limit}	None	3
Coefficient pass velocity	v_{eps}	Meters per second	0.5
Ball velocity	v_b	Meters per second	15
Diffusion coefficient	D	None	2.0
Pass probability	P_{ass}	None	0.2
Tackle probability	T_{ackle}	None	0.2
Side potential	U_b	None	80,000
Collision potential	U_c	None	20,000
Zone potential	U_z	None	20,000
First defender avoidance	U_e	None	8,000
First defender on the ball	U_d	None	10,000
Local potential	U_{loc}	None	1,000,000
Global potential	U_{glo}	None	1,000,000
Coefficent goal	g	None	50
Size of the field	l_x & l_y	Meters	80 & 120
Initialisation of agent position	l_{dx} & l_{dy}	None	-20 to 20 & -25 to 25

Figure 10. Illustration of the table presented in Feigean et al. (submitted). It is a summary of model parameters. The use of units relates to the non-dimensionality of certain parameters in the model.

COLLECTIVE BEHAVIOUR ANALYSIS

The analysis of the collective behaviour contained two specific steps: (1) the observation of the simulation and (2) the spatiotemporal data analysis. This section describes the spatiotemporal data analysis.

Computational metrics for football analysis

The spatiotemporal analysis was conducted according three different types of metrics: (1) a metric to measure the team centre, (2) a metric to evaluate the dispersion of the agents and (3) a metric to assess the expansion of the team. With a simulation study it is possible to compare the two types of individual adjustment modalities within a team, but also to compare them to a control team without any specific adjustment modality, to check whether both modalities involve collective changes. From all the simulations, the positions were collected for all agents over the modelled time. With positions (*x,y*), metrics give an overview of the spatiotemporal patterns of collective behaviour. The metrics used were defined as geometrical measures of the team centre, a stretch index to measure the dispersion of agents, and surface area to measure the team expansion.

Measure of the team centre. First, we calculated the geometrical centroid (*x;y*) to measure the mean position of all the agents. The geometrical centre of a team G is defined by this equation:

$$\begin{pmatrix} x_G \\ y_G \end{pmatrix} = \frac{1}{n}\begin{pmatrix} \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} y_i \end{pmatrix}, \quad (16)$$

where n is the number of agents, and x_i, y_i are the coordinates of an agent *i.*

Measure of the dispersion of agents. Second, we calculated the stretch index to measure the dispersion of agents. The stretch index is calculated as the mean distance of agents from the geometrical centre, which gives the compactness of the team. The stretch index, considering both axes, at given instant *t* was calculated by the following:

$$S_i = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i - x_G)^2 + (y_i - y_G)^2}, \quad (17)$$

where x_i, y_i are the coordinates of an agent *i*.

Measure of the expansion of the team. Finally, we calculated the convex hull to measure the surface area of the team. The surface area was calculated as the polygon with the least number of vertices that can circumscribe all of the team's agents, and where the potential vertices were given as the positions of the agents. Given a set of points, the following equation was applied to define the convex hull:

$$SA = \frac{(x_1y_2 - x_2y_1) + (x_2y_3 - x_3y_2) + \ldots + (x_iy_1 - x_1y_i)}{2}, \quad (18)$$

where x_i, y_i are the coordinates of an agent i.

CHAPTER 6 - EMPIRICAL STUDIES

STUDY 1 - AN EXPLORATORY QUALITATIVE STUDY OF INFORMATIONAL RESOURCES

Introduction. The aim of this study was to provide observations about the diversity of informational resources that can support players' activity when involved in spatiotemporal teamwork. Some works have gone further in specifying what the content of such informational resources could be. On one hand, informational resources have been considered local when a team member contributes to collective behaviour while adjusting to the immediate neighbourhood. On the other hand, some works state that informational resources can be global, grounded on the capability of any player to grasp the overall state of group behaviour. Nevertheless, the informational resources supporting an individual's contribution to collective behaviour have more often been theoretically presupposed rather than empirically investigated. In this line, Bourbousson and Fortes-Bourbousson (2016) have identified the lack of an empirical description of the regulation of interactions performed by team members in real time as a major gap in current teamwork research. To this end, we described the variety of informational resources accessed by team members during a football game. To conduct such a survey, we adopted an epistemological approach respectful of how humans actively regulate their agent–environment coupling (AEC), which was the enactivist approach to teamwork (De Jaegher & Di Paolo, 2007). From this perspective, sense-making was assumed to be central in delineating the dynamics of the AEC, and the phenomenological experience of the agent was seriously considered in the study design.

Methods. Eleven participants from one football team (i.e., national level) participated in this study. We video recorded a complete official game using a drone. A sequence of 10 minutes was selected, based on which phenomenological data were collected for all players through subsequent individual self-confrontation interviews. The verbal data obtained were transcribed verbatim, from which we reconstructed the way participants dynamically experienced the game, as players could comment on each instant of the activity under study. We then performed a thematic analysis (Braun & Clarke, 2006) to identify patterns of meanings within the verbalization data, leading to the characterization of various informational resources.

Results. From the 625 meaningful units of activity, we identified 625 singular informational resources that merged into 19 first-order themes, then merged into 12 second-order themes and finally merged into six third-order themes. The six third-order themes retained as accounting for the informational resources that supported participants' activities were as follows: (1) a single player, as captured from a focalised perception; (2) a global spatiotemporal shape, as captured from a bird's-eye viewpoint; (3) a single player associated with a global spatiotemporal shape, as captured from a perceptual sharing; (4) the ball area where current play is unfolding, as captured from a relocated focalisation; (5) surrounding behaviours, as captured from a comprehensive awareness; and (6) previously built knowledge suggesting an event expected to happen.

Discussion. Our study described a part of the complexity of regulating individual activity when contributing to teamwork. Such regulation was based on local and global informational resources, including the simultaneous co-occurrences of these resources and their divergence from knowledge-based modes of regulation. Alternating between focalised perceptions and open awareness and between nearby space and distant perceptions, players' supported their activities using diverse informational resources that were far more important than the ones that have been assumed in each of the frameworks available in the literature. This diversity should thus call into question the ecological dynamics framework, which presupposes the local nature of regulation implied in human activity, and thus, is largely unable to consider regulation modes that are distinct from local ones.

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Achieving teamwork in naturalistic sport settings: An exploratory qualitative study of informational resources supporting football players' activity when coordinating with others

Mathieu Feigean[a,*], Mehdi R'Kiouak[b], Roland Seiler[a], Jérôme Bourbousson[b]

[a] *Institute of Sport Science, University of Bern, Bern, Switzerland*
[b] *Laboratory "Movement, Interactions, Performance", Faculty of Sport Science, University of Nantes, France*

A R T I C L E I N F O

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Enactivist approach
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Interpersonal coordination

A B S T R A C T

This study aimed to provide a deeper understanding of the nature of informational resources that support team members' activities when contributing to spatiotemporal collective behaviour in real time. To this end, we conducted an exploratory qualitative study of a naturalistic football setting in which an *enactivist* approach to teamwork is employed. Ten professional football players participated in this study. Based on a continuous video recording of the participants' activities during an entire game and using phenomenological interview techniques, we performed a thematic analysis of the players' activities as experienced by them. Many situational resources have been highlighted based on the themes captured in the analysis; these have been categorised from local to global information and include the simultaneous use of these resources by the players. Only one theme reflecting knowledge-based resources did not cover situational resources. The results are discussed in terms of focalised *versus* broad awareness, nearby space-based *versus* relocated informational resources and local *versus* global informational resources.

1. Introduction

High-level performance in team sports is more than the mere sum of individual members' effectiveness. To understand how such team performances are built, the research on the topic has historically been driven by social psychology constructs and group dynamics constructs, such as leadership and cohesion (for reviews, see Carron, Bray, & Eys, 2002; Cotterill, 2012). However, considering that 'there is more to being an effective team than merely being a cohesive one' (McEwan & Beauchamp, 2014, p. 233), team effectiveness has been conceived as rising up primarily from the nature of the teamwork as achieved by team members (Eccles & Tenenbaum, 2004). Teamwork is a type of team process that focuses on members' activities. Nevertheless, group dynamics constructs developed in previous research are considered related to teamwork but not synonymous (Eccles & Tenenbaum, 2004; McEwan & Beauchamp, 2014).

More specifically, teamwork is defined as 'a dynamic process involving a collaborative effort by team members to effectively carry out the independent and interdependent behaviours that are required to maximise a team's likelihood of achieving its purposes' (McEwan & Beauchamp, 2014, p. 233). Teamwork is also viewed as accounting for what teams do (Martin, Carron, Eys, & Loughead, 2012) rather than what teams feel or believe. In this light, describing what team members do, how they behave on the field, and how they achieve team coordination in real time has been a main topic in team sport research in recent years (for a review, see Araújo & Bourbousson, 2016).

Three main theoretical frameworks propose hypotheses about how teamwork is achieved in team sports. The first is the social-cognitive approach (Eccles & Tenenbaum, 2004), which assumes that teamwork is predicated on the notion of team cognition. A key aim has been to understand how shared knowledge can help team members coordinate efficiently in adapting to the dynamic demands of competitive performance environments. The assumption of shared knowledge results from the team members having complementary goals, strategies, and relevant team routines that provide basic shared expectations about each other's actions. This allows them to coordinate and disregard completely new situational analyses of how the team should face unfolding game events. The social-cognitive approach was mainly discussed and challenged due to the primacy given to the shared knowledge hypothesis (Silva, Garganta, Araújo, Davids, & Aguiar, 2013) and accused of not accounting enough for the situated nature of teamwork. Thus, missing the embedded and embodied nature of human cognition (Froese & Di Paolo, 2011), the social-cognitive approach to teamwork neglected the key role of ongoing interactions in patterning collective

* Corresponding author.
E-mail address: mathieu.feigean@orange.fr (M. Feigean).

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behavioural states (Cooke, Gorman, Myers, & Duran, 2013).

The second approach to teamwork is the ecological dynamics framework (Araújo, Davids, & Hristovski, 2006), according to which team behaviour can be investigated in terms of its own dynamics without investigating individuals' internal cognitive processes on a micro level. Teamwork (i.e., the interpersonal interaction process leading to team behaviour) is considered to occur between biological rhythmic units that are connected informationally (Araújo & Davids, 2016). Such informational connections between team members are assumed to be driven by *affordances* (i.e., opportunities for action; see Gibson, 1979). The concept of affordances presupposes that the environment is directly perceived in terms of what actions a performer can take and is not dependent on the players' expectations or mental representations (Richardson, Shockley, Fajen, Riley, & Turvey, 2008). On a social level, shared affordances are assumed to govern the arrangement of many individual behaviours (Silva et al., 2014); thus, teamwork depends on the team's collective perceptual attunement to a landscape of environmental constraints. Therefore, based on their situational perceptual readiness, players become capable of refining their behaviours to functionally adapt to what they perceive as team coordination opportunities. In such a view, teamwork-related concepts (e.g., division of labour; Duarte, Araújo, Correia, & Davids, 2012) have been investigated based on the assumption that interpersonal patterns that are observable at the behavioural level are sufficient to reveal the key environmental constraints that underlie team coordination. While acknowledging the main role of situated interaction between team members in helping collective behaviour emerge, the ecological dynamics approach has been analysed as reflecting an ontological 'realism' (Varela, Thompson, & Rosch, 1991) in that it considers affordances as existing in the real material/physical setting and views them as something that can be revealed through behavioural methods. In contradiction with such a view, some authors have considered humans as primarily coupled to a meaningful world rather than to a physical one (Varela et al., 1991). The ecological dynamics approach to teamwork rejects the description of what team members live in real time when coordinating with others, thus missing the meaningful nature of any affordance and the underlying sense-making activity that helps affordances emerge (Fultot, Nie, & Carello, 2016). In other words, if individual behaviour is embedded in the environment, it is achieved in a field of affordances that should be investigated by considering the ongoing actors' own world that is, how each member singularly builds and experiences his or her world (Rietveld, Denys, & Van Westen, 2016).

The third framework adopted here takes into consideration these critiques. It allows a description of how ongoing collective behaviour and its dynamics are situated and managed online by the interactors, while being respectful of the singular meaningful involvement of each team member. It is called the enactivist approach to teamwork (De Jaegher & Di Paolo, 2007). This framework defends a nonrepresentational conceptualisation of social cognition (Maturana & Varela, 1980; Varela, 1979). Defending the need of considering the phenomenological experience of participants, the enactivist approach states that a given player's 'own world' is the principal component of his or her situated and embodied activity. Contributing to a form of empirical micro-phenomenology (Kimmel, Hristova, & Kussmaul, 2018; Theureau, 2003), the enactivist approach to teamwork aims at describing the meaningful world of actors when being coupled to their naturalistic environment, including other team members. This form of phenomenology allows the production of descriptions of activity that are not limited to the third-person point of view (i.e., as performed from the researcher's point of view; Varela & Shear, 1999). It has thus been introduced as a promising alternative to computationalism in psychology (Varela, 1988).

Investigating the activity at a prereflective level of consciousness (i.e., as it is primarily experienced by the subject; Legrand, 2007), researchers' ontological involvement has been to consider subjects' lived experiences as the main phenomenon allowing a given activity to be regulated in real time and thus to exhibit directedness in an environmental coupling loop. Adopting a so-called ontological relativism (Smith & McGannon, 2017) and inspired by philosophical developments in phenomenology (for such an elaboration, see, e.g., Laroche, Berardi, & Brangier, 2014), it is assumed that people's 'own world' is simultaneously produced by three components: (1) the product of the nature of their sensory apparatus as it is genetically inherited (e.g., Von Uexküll, 2010), (2) the history of the actor/environment coupling as it is observable in recurrent patterns of perception and action built during individual development, and (3) the way in which each individual experiences his or her coupling with the environment in the moment (e.g., Di Paolo & Thompson, 2014). While being phenomenology-inspired, enactivism is different from other philosophical-inspired sport studies referring to phenomenology (e.g., existential phenomenology, Allen-Collinson, 2009; Dale, 1996; see Martínková & Parry, 2013 for a global picture of the field). Whereas traditional phenomenology invites to document athletes 'being in the world' (i.e., their existential involvement in their sporting practice), enactivism is focused on investigating very specific actions, as experienced in the real-time (i.e., the situated enacted world a given athlete experience, as embedded in a given very singular situation). This last aspect has important epistemological consequences: It makes the situated experience lived by each performer the *sine qua non* condition for describing how interactors' behaviours are systematically arranged into dynamic patterns in their real-time activity. In this light, enactivist researchers from sport science built data collection techniques dedicated to reconstructing the perspective from which individuals regulate their own and collective activity in real time and in their naturalistic setting (Poizat, Sève, & Saury, 2013), through data collection techniques dedicated to help athletes to comment specific and very singular actions. In this light, researchers explored the micro-phenomenology of action by building verbalization protocols dedicated to document the lived experiences of athletes at a given instant of their activity (e.g., Kimmel et al., 2018). Related phenomenological forms of interviews thus aim to help participants to reenact their situated own world related to a given singular action (e.g., explicitation interview), sometimes making a methodological use of video recording to stimulate the participant's recall (e.g., self-confrontation).

In sport science, such an enactivism has been fruitful in showing how qualitative descriptions of sport activities offer a counterbalance against current behavioural theories (Poizat et al., 2013). Regarding teamwork investigation, the approach has been mobilised in the analysis of the joint action of rowers (R'Kiouak, Saury, Durand, & Bourbousson, 2016), basketball players (Bourbousson, Poizat, Saury, & Sève, 2012), and table tennis teammates (Poizat, Bourbousson, Saury, & Sève, 2009). From the current state of the research, and in line with how the enactivist approach to teamwork is applied, Bourbousson and Fortes-Bourbousson (2016) have identified the nature of the regulation of interactions performed by team members in real time as a major gap in current teamwork research. This regulation comprises the way players adapt their own behaviour to their current lived experience of the collective joint effort and the team's needs (De Jaegher & Di Paolo, 2007). The gap reveals that the description at a behavioural level of how team coordination is formed, stabilised, and/or destroyed is far more developed than the description of how individuals live their own interactions and regulate their teamwork in real time in relation to what they perceive as the team's behavioural needs. In real time, the way the teamwork activity of a given team member unfolds is supported by informational resources accounting for the team's dynamic behaviour (i.e., What is the subject attuned to in the ongoing activity in this moment?). These informational resources appear to the team member from his or her viewpoint; they are not fixed but change over time, depending on the current needs of the actor and on the unfolding events he or she is able to grasp (De Jaegher & Di Paolo, 2007). However, informational resources supporting an individual's contribution to collective behaviour have more often been theoretically presupposed (i.e., as they were in the ecological dynamics and social-cognitive frameworks) than empirically investigated (Bourbousson & Fortes-Bourbousson, 2016).

Nevertheless, some works have gone further in specifying what the content of such informational resources could be, investigating how they can support individual activity and how they contribute to patterning collective behaviour. On the one hand, informational resources have been considered local when a team member contributes to collective behaviour while adjusting to the immediate neighbourhood (Silva et al., 2014). Local informational resources account for players coordinating based on what they perceive of others' individual behaviours, disregarding the higher-order shapes that emerge from the many interpersonal couplings within the team. In this case, team behaviour is explained through elementary mechanisms, suggesting that it is derived from a simple arrangement of local interactions without the need for players to be attuned to the overall team coordination they help develop. Many researchers have suggested that team sport players' coordination activity might be supported by information available in players' nearby space only (i.e., local information). The given variables were proposed to rely on a given interpersonal distance variability (Passos et al., 2011, in a rugby union), a given player's velocity (Passos et al., 2008, in a rugby union), or a player's trajectory, as in the case of an attacker–defender dyad where interpersonal angles are suggested to shape decision making (Araújo et al., 2006, in basketball). In such works, viewing informational resources as local allowed the authors to illustrate how the parsimonious processes leading to swarming behaviours observed in nature (i.e., in social insects or fish) can inspire sports research. It also led the authors to reinforce the relevance of affordance-based approaches to team coordination in sport, postulating that spatiotemporal sporting teamwork can unfold through elementary and nonrepresentational mechanisms.

On the other hand, some works have stated that informational resources can be global, grounded on the capability of any player to grasp the overall state of group behaviour. For instance, researchers have stated that "understanding these reciprocal relationships between the state of movement of the two dimensions of opposition (offense vs. defense) and knowing how they operate in real game-play, constitutes, by definition, tactical intelligence with regards to opposition" (Grehaigne, Godbout, & Zerai, 2011, p. 763). In this view, a given player's positioning activity is based on high-level information related to the global picture that the team achieves in real time. This capability has been introduced as particularly powerful in cases where collective behaviour is goal directed and where players are concerned with monitoring the emerging team behaviour in real time (Bourbousson & Fortes-Bourbousson, 2016). While this kind of informational resource is discussed less, some recent empirical evidence has illustrated how global informational resources can support team members' contributions to teamwork. For instance, expert basketball players' decisions about dribbling to the basket are shown to be better explained by global-level parameters (i.e., relationship between geometrical centres of the teams) than by local-level ones (i.e., attacker–defender relationship; Bourbousson, Deschamps, & Travassos, 2014). The results of this previous study suggested that individual players are capable of adjusting their behaviour by considering the global movement of team members, at least in the case of the ball carrier initiating a critical action.

The design of the present study takes into consideration the fact that research describing the kind of spatiotemporal information that can support individual team members' real-time activity is scarce. While isolated studies have provided evidence of a spectrum of informational resources (i.e., categorised as local and global), the nature of such resources was mainly theoretically presupposed rather than empirically described (Bourbousson & Fortes-Bourbousson, 2016). When the study was empirical, it only proposed one way of using informational resources, to act, that was players' activities supported either by local or global spatiotemporal informational resource, separately. No exploratory study has aimed at describing a broader spectrum of spatiotemporal attunement possibilities and how such possibilities would occur together in a complex naturalistic setting. Therefore, the present exploratory study aims at providing a deeper understanding of how team members are dynamically attuned to the team coordination needs of their joint effort in real time.

Thus, following Bourbousson and Fortes-Bourbousson's (2016) recommendations, our study design should be beneficial in terms of conceptual and applied gain. In terms of applied gain, we expect to provide coaches with opportunities to redesign their training practices while being aware of the number of skilful activities their players can exhibit that involve interacting with the others' movements in real time. In terms of conceptual gain, we expect our delineation of the notion of informational resources to be more fruitful than existing notions, in terms of the empirical descriptions provided—that is, shared knowledge on the one hand (as presupposed in the social-cognitive framework) and shared affordances on the other hand (as presupposed in the ecological dynamics framework). Assuming that the actor's own world is self-determined in the course of action, the enactivist approach to teamwork remains quite open to what a team member should be attuned to.

In addition, our study was conducted with many team members, following Bourbousson and Fortes-Bourbousson's (2016) recommendation that the number of players involved in the collective behaviour matters. The many studies (naturalistic and experimental) investigating team coordination in dyads were probably unable to capture the complexity of the active regulation of interacting behaviour in social systems, especially when aiming to debate the local versus global nature of the informational resources.

2. Methods

2.1. Participants and procedure

A football match was selected as the study setting. It offers a larger number of team members that can be studied and therefore provides more possibilities to observe a range of informational resources that support participants' real-time activities as embedded in multiple spatiotemporal levels of team organisation.

Ten French male professional football players (aged 26.1 ± 4.01 years; experience playing football = 19.80 ± 4.15 years) from the same team playing in the fifth football league in France volunteered to participate in this study. To preserve confidentiality, letters and numbers were used to identify the players: D1 to D4 were defenders, M5 to M7 were midfielders, and A8 to A10 were attackers. The first author was involved in ethnographic participative time in the month preceding the data collection. This period aimed at building a mutual familiarity between the researcher and the participants and at better contextualising the single official football match that was selected for the study. At the time of the given match, the team was ranked sixth in the league. The team won the previous game, so the team members remained quite confident about the coaching strategy. The match under study ended with a final score of 0–0.

The study was performed in accordance with the Declaration of Helsinki and the American Psychological Association ethical guidelines. The Bern faculty's ethical committee approved the study. All participants were informed of the study procedures and gave written consent.

2.2. Data collection

Behavioural and verbal data were collected for this study. For the former, players were video recorded for the entire game using a drone (DJI Phantom 4, full HD, 50 fps) positioned around 6 m above the side of the pitch. A wide-angle lens was used and permanently adapted to simultaneously and continuously capture all the movements of the participants and their opponents. This data helped in building a behavioural account of the game. It also supported interviews dedicated to the collection of verbal data. Based on the authors' experiences of working in team sports, the calibration of the camera was carefully adjusted to facilitate the self-confrontation interviews that were conducted afterwards (i.e., the camera viewpoint helped participants re-experience their game and describe their activity).

The verbal data were gathered from individual phenomenological postgame interviews with each of the participants (i.e., individual self-confrontation interviews, detailed below) conducted as soon as possible after the game (i.e., within 48 h). The first and second authors performed the interviews; both are experts in the required interview techniques and had previously conducted such interviews. Each participant was interviewed about the same sequence corresponding to the 65th to 75th minutes of the game. The coach selected this sequence immediately after the game when asked to delineate a section of the game illustrating teamwork quality. The coach described it as signifying players' high involvement in a joint task effort. This choice was validated by the researcher due to a lot of salient events (e.g., corner kick, off side, direct free kick, and yellow card) that were considered opportunities for helping players to remember their game and comment on the sequence in the detail. This choice was also confirmed by the players: When invited to freely comment on the portion of the game selected, the players reported a satisfying team performance (e.g., feeling of togetherness; every player involved in the collective behaviour principles). Based on previous research (e.g., Bourbousson, Poizat, Saury, & Sève, 2011; Bourbousson et al., 2012), 10 min of activity was considered a representative sample appropriate for obtaining data saturation in the qualitative analysis of the verbal dataset. All interviews were recorded using a video camera and a tape recorder. Individual interviews lasted between 39 and 62 min (45.37 ± 6.57 min).

The applied self-confrontation interview techniques referred to specific forms of phenomenological stimulated recall. Also called *enactivist interviews* (Rochat, Hauw, Antonini Philippe, von Roten, & Seifert, 2017), self-confrontation is dedicated to facilitating the expression of participants' prereflective self-consciousness, as experienced during the real-world activity under study. Prereflective self-consciousness reveals people's capacity to account for their own activity and to grasp the reality in which they were immersed. This technique is consistent with the enactivist approach adopted in team sports (for scientific accounts obtained using this technique, see Bourbousson et al., 2012) and affords special attention to the implicit ways in which a given player experiences an ongoing activity. It illustrates the claim that individual activity reveals autonomous characteristics that are not reducible to behavioural descriptions (Maturana & Varela, 1980). During the self-confrontation interviews, each participant viewed the videotaped game with the researcher. The tape was stopped by the researcher or the participant as often as needed so that every specific action in the game (e.g., moment of ball control, dribble, and passing) was scrutinised. At every instant, the participant was asked to 're-experience his game' (i.e., reenact his game) to describe and comment on the details of the dynamics of the lived experience at each point (i.e., what happened for him at the given instant and what he was doing, feeling, thinking, and perceiving). Methodological precautions (similar to those recommended by Trudel, Haughian, and Gilbert (1996)) were used to prevent participants from making inferences or generalising about their thinking (for further details, see also Theureau, 2003).

To characterise the nature of the informational resources supporting the individual activity of coordinating with others, our data collection was clearly respectful of the ontological relativism underlying the enactivist approach. The interview questions did not directly address the nature of the informational resources supporting the individual activity of coordinating with others, so we preserved as well as possible the open expression of the participants' lived experiences. Questions were related to the players activities when they were physically engaged in adjusting their displacements to each other, according to the collective spatiotemporal needs they perceive. For this reason, the moments when the game was interrupted (e.g., after referee's toot) in which players could move to communicate to each other were not examined. Thus, players' activities under study were essentially driven by the situational understanding each player built on the game, based on the singular perception each of them had of occurring events, or on the knowledge-based expectations he was able to exhibit in the real-time. These elements that supported their activities were considered informational resources and were the focus of the analysis.

2.3. Data processing

Using the video and based on the selected sequence, we carried out a comprehensive behavioural description (Table 1). This step consisted of noting the ball carrier at each moment in time, players' positions near the ball, and the spaces that were particularly dense in terms of players and those that were relatively free. Other observable football-related events were reported when salient (e.g., defensive errors and stealing the ball).

Verbal data obtained during self-confrontation interviews were fully transcribed verbatim by the first author, including unfolding details in the interview (e.g., noting the participant's salient observable behaviour during the interview and/or breaks and hesitations), and checked against the tapes for accuracy (Braun, Clarke, & Weate, 2016). All the transcriptions were read a couple of times and annotated for a deep familiarisation (Braun et al., 2016). Four main steps organised the analysis. The first two steps were specific to our activity-centred framework; the subsequent steps followed the principles of thematic analysis (Braun & Clarke, 2006; Braun et al., 2016): (1) step-by-step accounting of the way participants singularly reported their experience of the game dynamics, (2) delineating meaningful units of activity (MUAs) as identifiable within each participant's experience report, (3) coding the singular informational resource (SIR) supporting each MUA, and (4) developing themes through clustering SIRs. Steps 2 and 3 were conducted by two researchers (the first and the fourth authors) on a data sample selected for critical dialogue. When both agreed on the way MUAs and SIRs should be identified, the remaining data were processed by the first author only (for a discussion about the epistemological conditions of such a procedure, see Smith & McGannon, 2017). Step 4 was performed by the first author only and was challenged at each iteration by the fourth author acting as a critical friend (Smith & McGannon, 2017).

While informed by a constructivist epistemology (i.e., considering that a researcher cannot build theory-free knowledge), the method exposed here reflects an inductive processing. Our aim was to obtain an exploration of the informational resources supporting team members' teamwork-related activities that was, as much as possible, data driven.

2.3.1. Step-by-step accounting of the way participants singularly reported their experience of the game dynamics

Based on the collected verbal data, we were able to further characterise how the participants experienced each instant of their game. We first reconstructed the way participants dynamically experienced the game by synchronising in time the behavioural description of the game with the related portions of the verbal scripts of each participant. From this procedure, we obtained a timeline of verbalisations that were assumed to be the expression of the way in which the activity was experienced by each participant. As the behavioural description was common to all participants, this procedure provided a synchronisation of participants' overall verbal data.

2.3.2. Delineating MUAs as identifiable within each participant's experience report

Based on the timeline of verbalisations obtained, this step consisted of recognising the data relating to the study aim while identifying how such data were related to one or more meaningful discrete units of

Table 1
Examples of verbalisations collected from self-confrontation interviews and the related meaningful units allowing us to build the singular informational resource (SIR) and themes, as obtained from various participants' (i.e., A3, D3, M7, and M5) verbatim transcripts at several moments of the game.

Time	Time Code	Behavioural Description	Verbatim's Extract	MUA (n)	SIRs (n)	First-order Theme	Third-order Theme
5′27″	60	- The team is in attack phase. - The ball-carrier M6 is in the middle of the field. - M6 is not on a time pressure. - M6 easily moves forward with the ball.	Researcher: Now he [one of his midfielder, M6] receives the ball… what is important to you now? D3: *"You know at this time, I'm still waiting, I see that our team is quite forward on the field, thus I decide to stay in my place and follow the movement."* Researcher: What do you mean by movement? D3: *"Actually, we move forward together."*	The player is aware of the team's positioning and collective forward movement (170)	Perception team positioning and collective movement (170)	Perception of spatiotemporal state of the team	Informational resources relying on a spatiotemporal shape, as captured from a bird's-eye viewpoint
6′22″	73	- There is a long pass for the opponent attacker. - Two partners in defence (D1, D2) are moving to the opponent ball carrier. - The teammate goalkeeper is talking. - It is potentially goal action.	Researcher: Here in this situation [there is a long pass for the opponent attacker] what are you thinking at this time? M7: *"I think I will come back, actually I'm focus on the ball and tried to get closer to the ball, even if I'm not really important here I stay focus on the ball because if one of my defender catch the ball I need to be ready."*	The player is focus on the ball, observing when the ball would be passed (46)	Focusing on the ball and the moment of the pass (46)	Focusing on the trajectory and movement of the ball	Informational resources relying on the ball area where current play is unfolding, as captured from a relocated focalization
8′43″	95	- M5 receive the ball. -M5 is just behind the middle line of the field. - M5 is not on time pressure.	Researcher: You receive the ball… what is going on for you now? M5: *"Now when I receive the ball, I'm looking everything around, I keep the ball until to see the near situation is going to be better, at this moment I see no one is free for a pass."*	The player is looking every event around, without being focused on a specific element (129)	Unfocused perception of surrounding behaviours. Looking what is going on around (129)	A broad and non-directed perception of what happens near to the player	Informational resource relying on proximal surrounding behaviours, as captured from a comprehensive awareness

Note: MUA, meaningful units of activity; SIRs, singular informational resources.

experience. In this light, only the portion of participants' activities relating to how they contributed to creating, maintaining, or changing a part of or all the ongoing spatiotemporal collective behaviour was first retained. Within such portions, we identified discrete MUAs. An MUA was considered when it formed a consistent unit from the viewpoint of the given participant, not in terms of the ideas expressed by the participant in his verbal report but in terms of the action performed that he was commenting on. Each MUA thus reflected an instant of activity, and this activity was related to regulating collective behaviour. An MUA started with the participant experiencing a new setting and ended with the beginning of a new one. MUAs last around two seconds on average. For instance, we delineated an MUA in the following verbalisation extract: '*A9 is getting the ball. I'm looking at what he is doing with the ball. At this moment, I'm moving to him to be closer. I'm totally focused on him …*'. During the sequence under study, 625 MUAs were identified across all participants. The distribution was as follows: D1 = 60 MUAs, D2 = 63 MUAs, D3 = 67 MUAs, D4 = 57 MUAs, M5 = 69 MUAs, M6 = 66 MUAs, M7 = 68 MUAs, A8 = 58 MUAs, A9 = 63 MUAs, and A10 = 51 MUAs.

2.3.3. Coding SIRs supporting each MUA

The aim of this step was to characterise the SIRs that supported each instant of activity delineated in the previous step (i.e., identifying the SIRs within each MUA). A SIR is defined as the elements that are significant for a given team member at a specific moment and account for what informational resources the participant considers while acting. We identified SIRs by asking the following questions about the collected and transcribed data: What is the meaningful element supporting the player's activity? What element is the player considering? One SIR was identified for every MUA. SIRs were labelled while trying to preserve their complexity, especially when composed of many simultaneous perceptions. This step gave rise to 625 SIRs. For instance, in the excerpt '*I'm just getting the ball on the middle field, so I'm moving forward. I see that A10 is in a good position to receive the ball, so I'm focusing on him …*', the identified SIR was labelled 'A10 is in a good position, as captured from a focalisation on A10 behaviour'.

This analysis was performed for each participant's chain of MUAs and was then aggregated across the overall participants to provide a general account. At this stage, each SIR was labelled in a manner that respected the singular experience that each participant verbalised. Three rounds of coding were needed to refine the existing codes, ensuring the homogeneity of SIR identification and formulation. While our coding procedure was considered mainly semantic (obvious meanings expressed by participants; see Braun & Clarke, 2006, for details), some SIRs were not totally or explicitly commented on by the participant (i.e., latent), requiring the researchers to infer the SIRs from a comprehensive analysis of the participant's lived experience by scrutinising preceding and subsequent MUAs in addition to the behavioural description of the game events. Less than 5% of the total SIRs identified required inferences by the researchers.

2.3.4. Developing themes through clustering SIRs

Finally, we merged SIRs identified in the previous step into related themes (Braun & Clarke, 2006). This process consisted of searching for patterns (i.e., commonly recurring themes) in the 625 identified SIRs. The first step consisted of grouping the 625 SIRs into larger categories, also called first-order themes. This step involved two criteria: (a) first-order themes must be exhaustive—that is, each SIR must be included in a first-order theme[1]; and (b) first-order themes must be exclusive, implying that their labelling (and their content-related definitions) must be sufficiently discriminating so that no SIR could fit with two first-order themes (i.e., no overlapping across themes). Each time a new SIR was processed to further delineate first-order themes, the previous provisional themes could be changed and rearranged, thus giving rise to new themes and/or the removal of themes. In this step, we aimed at developing themes that were internally coherent, consistent, and distinctive (Braun & Clarke, 2006). This procedure included the specific work of naming the themes so that each wording retained did not change the underlying logics of clustering, while respecting the participants' singular phenomenology.

Data saturation (for details, see Fusch & Ness, 2015) was obtained after processing the first six players (i.e., 378 SIRs), which means that no rearrangement of the first-order themes was required, and the entirety of the remaining SIRs perfectly fit with the existing proposed themes. From this step, 19 first-order themes were identified.

In the second step, due to the number of first-order themes identified, we performed a second round of thematic analysis applied to the first-order themes. This step was similar to the previous one and aimed at identifying higher-level patterns into which first-order themes could fall. From the 19 first-order themes, 12 second-order themes were obtained. This second process was considered a methodological step and will not be further reported in the results section. In the final round of thematic analysis, six third-order themes were obtained. The obtained three levels of themes were considered relevant in that they match the recommendation of Braun et al. (2016) for a final three-level structure made of subthemes, themes, and overarching themes. Third-order themes (i.e., overarching themes) were retained as 'informational resources' for discussion.

In each round of thematic analysis, the initial SIRs were carefully checked so that the final third-order themes related well to participants' real-world experiences of the game. An analysis of the specific occurrences of each informational resource within each player's course of experience was then performed, first to enable the most prominent themes to be identified and second to show how such informational resources were observed in each of the participant's activities.

3. Results

3.1. Identification of the informational resources supporting participants' activities

From the 625 MUAs, we identified 625 SIRs that merged into 19 first-order themes (not detailed here) and then merged into 12 second-order themes and finally merged into six third-order themes, on which we elaborated below. Table 2 shows the hierarchy of themes and information about their relative prevalence.

The six third-order themes retained as accounting for the informational resources supporting participants' activities were as follows: (a) a single player, as captured from a focalised perception (T1); (b) a global spatiotemporal shape, as captured from a bird's eye viewpoint (T2); (c) a single player associated with a global spatiotemporal shape, as captured from a perceptual sharing (T3); (d) the ball area where the current play is unfolding, as captured from a relocated focalisation (T4); (e) surrounding behaviours, as captured from a comprehensive awareness (T5); and (f) previously built knowledge suggesting an event expected to happen (T6). The following sections detail the players' lived experiences under the six retained themes (Fig. 1). To illustrate a given identified informational resource, we mention the related underlying first-order themes assumed to provide phenomenological content similar to the team members' real-world lived experience. Moreover, we provide related verbatim excerpts illustrating the supporting data obtained from the self-confrontation interviews.

3.1.1. Informational resources relying on a single player, as captured from a focalised perception (T1)

This theme indicated that the participant adapted by being highly focused on a single player. It showed that the participant was focused

[1] While Braun et al. (2016) suggested that this criterion is not always required, we still applied it after deciding that our dataset was previously made clean enough, especially through MUA identification.

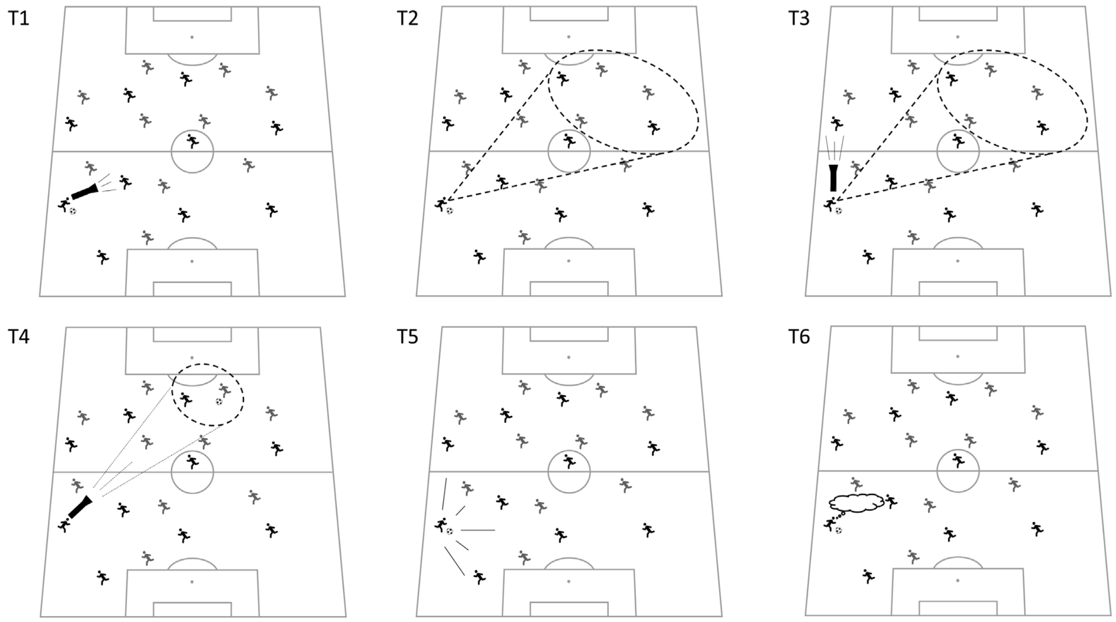

Fig. 1. Informational resources supporting the players' activities at a given instant within a team; a single player, as captured from a focalised perception (T1); a global spatiotemporal shape, as captured from a bird's eye viewpoint (T2); a single player associated with a global spatiotemporal shape, as captured from a perceptual sharing (T3); the ball area where the current play is unfolding, as captured from a relocated focalisation (T4); surrounding behaviours, as captured from a comprehensive awareness (T5); and previously built knowledge suggesting an event expected to happen (T6). The following sections detail the players' lived experiences under the six retained themes (Fig. 1). To illustrate a given identified informational resource, we mentioned the related underlying first-order themes assumed to provide phenomenological content similar to the team members' real-world lived experience. Moreover, we provided related verbatim excerpts illustrating the supporting data obtained from the self-confrontation interviews.

on the trajectory or the attitudes of the single player. Informational resources in this theme included the following typical underlying first-order themes: focusing on the attitudes of the ball carrier teammate, focusing on the attitudes of a ball carrier opponent, focusing on the trajectory of a non-ball-carrier teammate, focusing on the trajectory of a non-ball-carrier opponent, and focusing on the interpersonal distance that separated the given player from another team member (see Table 2). The following excerpts relate to one of the participants' experiences during the game, including the related behavioural description (see step 1 of the method):

> *'A10 gets the ball; I'm totally focused on him. I have a look at his trajectory to adjust my movement. I'm running very fast; I'm late.'* (*player = A9/time code* (*n*) *= 5/MUA = 314/first-order theme 1.1*) *[M5 passes the ball to A10. The team is on the attack and moves forward to the opposite goal. A10 just receives the ball near the goal, on the right side of the field.]*

> *'This player [non-ball-carrier opponent] becomes important for me. I'm following him by keeping my gaze on him because he is now dangerous. He can receive the ball and go straight to the goal. I'm following his trajectory.' (D3/8/143/1.4) [An opponent attacker receives the ball near the goal, on the right side; several team members (defenders) are around the ball, and one is especially defending the opponent ball carrier. D3 is on defence but not near the ball on the centre of the field. One non-ball-carrier opponent is close to him.]*

3.1.2. Informational resources relying on a spatiotemporal shape, as captured from a bird's eye viewpoint (T2)

This theme showed that the participant adapted by being attuned to the collective behaviour, which consists of an ensemble of players. In this case, the given participant viewed the team as a whole or considered both teams together as a unitary whole, as a given subgroup of players could also be. Players' activities supported by a perception of a global spatiotemporal shape were often sensitive to the occurrence of a free area or a high density of players. Informational resources in this theme included the following typical underlying first-order themes: perceiving the spatiotemporal state of the team, perceiving the behaviour of a small collective unit (e.g., the defenders and the attackers), perceiving a free area that affords a possibility of action, perceiving a high density of players in a given area of the field, and perceiving the configuration of the instantaneous power balance between both teams (see Table 2). Together, these elements accounted for informational resources relying on a global shape and/or the movement of a collective unit of many players. The following excerpts from the self-confrontation interviews illustrate this theme, including the related behavioural description:

> *'In this situation, how I'm placed on the field, I'm totally looking for a free space behind the opponent defenders. I see the free space between defenders, and I move forward to get it; actually, the coach always told me to go to the free space.' (A10/1/199/2.3) [D3 receives the ball; he is alone without time pressure in his defending area. A10 is on the attack in the opponent defence area.]*

> *'I see my team members, and I especially focus on the overall middle players and how everyone is placed on the field. In fact, at this time, I am thinking that they are too far away from me but also from each other.' (M5/4/68/2.2) [D4 performs a wrong long pass to the opponent defence. An opponent midfielder receives the ball, and the ball leaves the pitch. An opponent is currently ready for the throw-in.]*

3.1.3. Informational resources relying on a single player associated with a spatiotemporal shape, as captured from a perceptual sharing (T3)

In this theme, participants reported a perceptual sharing, and their activity was therefore experienced as the hard task of monitoring and combining two distinct informational resources. In detail, the theme showed the complexity of combining different informational resources in real time. In such a case, participants actively monitored several sections of the game simultaneously to enhance their decision-making accuracy. Informational resources in this theme included the following typical underlying first-order themes: simultaneous perception of many players' movements on one side and a focalisation on the attitudes of a single player on the other side, simultaneous perception of the ball carrier on one side and the spatiotemporal state of a small social unit, simultaneous perception of a given player's behaviour and the current area where the play is unfolding, and simultaneous perception of a given player and one or more other players located in a very distinct area of the field (see Table 2). Together, these elements account for informational resources relying on different targets. The following quotes illustrate this theme, including the related behavioural description:

'I'm just looking at what he is doing [the middle opponent ball carrier is near] with the ball, and I'm also checking the configuration of my team attackers. I see they are not placed well; they cannot avoid an easy pass for the ball carrier, and I'm looking if they can move fast to avoid a pass. Actually, at the same time, I'm looking at the ball carrier because he also has the possibility to move forward quickly.' (M5/7/71/3.2) [The middle opponent ball carrier is quite free and just received the ball in the middle of the pitch from an opponent defender. The middle opponent is ready to run forward.]

'The opponent team is moving forward, and I see that they are coming quickly. I'm checking the moves of the opponent team and I'm pursuing focusing on my central defender to be sure we are moving together and keeping a short distance between us.' (D1/7/255/3.1) [The middle opponent ball carrier is quite free and just received the ball in the middle of the pitch from an opponent defender; the middle opponent is ready to run forward.]

3.1.4. Informational resources relying on the ball area where the current play is unfolding, as captured from a relocated focalisation (T4)

This theme accounted for the participants' capability to be focalised on a ball area that was far from their own location. Participants commented on this theme by explaining how no specific player was significant but that all their sensitivity was directed towards occurring events in a given ball area. In this case, those events were the ongoing game events around the ball that grounded such an awareness. Informational resources in this theme included the following typical underlying first-order themes: focusing on the trajectory and movement of the ball and focusing on the players' behaviours around the ball (see Table 2). These elements account for participants having an activity based on their exclusive perception of what happens near the ball, whether it is near or far from their own location on the field. The following excerpts illustrate this theme, including the related behavioural description:

'Now I'm focusing on the movement of the ball. I'm starting to participate, and I will thus move to the ball. I'm not really concerned about the players. I'm not well placed to defend, so I focus on the ball to see if the game will come back to the left side.' (M7/8/5/4.1) [An opponent attacker receives the ball near the goal, on the right side; several team members (defenders) are around the ball, and one is especially defending the opponent ball carrier. D3 is on defence but not near the ball on the centre of the field. One non-ball-carrier opponent is close to him.]

'I'm looking at the ball and the players around it; lots of players are near the ball on the right side, so I'm checking what's going on down there around the ball.' (M5/8/72/4.2) [An opponent attacker receives the ball near the goal, on the right side; several team members (defenders) are around the ball, and one is especially defending the opponent ball carrier. D3 is on defence but not near the ball on the centre of the field. One non-ball-carrier opponent is close to him.]

3.1.5. Informational resources relying on proximal surrounding behaviours, as captured from a comprehensive awareness (T5)

This theme accounted for informational resources that were built from a viewpoint that participants experience as being in a 'radar/scanner' modality of perception, which was described as a comprehensive and nonfocused scan of the proximal space. The participants stated that in such a radar mode, they scan everything happening within their proximal vicinity without being focalised so that they can grasp any sudden event in the nearby space that could afford a possibility of action. In terms of perceptual content, this mode included informational resources relevant to interpersonal distances, nearby players, the number of players in the proximal space, and the position of the immediate opponents or one's team members. The informational resource in this theme included the following typical underlying first-order theme: a broad and nondirected perception of what happens near the player (e.g., ball, players, and free spaces and distances around the players; see Table 2). The following excerpts illustrate a participant's activity during the game, including the related behavioural description:

'I'm not focalised on something. Many of my team members are around me. I say to myself that an opportunity for an easy pass should appear next. I'm waiting for a free partner, so I'm looking at each of them quickly, then I keep and protect the ball until …' (M5/11/74/5.1) [The team is on the attack; M5 just received the ball from A9 from a head pass.]

'M5 is here and I see two opponents near me. There are five of us defending here. I feel that I'm not in a good place. I'm still looking around to move to a good place according to all the people around me.' (M7/19/15/5.1) [The team is on defence; M7 looks behind him and moves on the pitch.]

3.1.6. Informational resources relying on previously built knowledge suggesting an event expected to happen (T6)

This theme accounted for informational resources that did not directly rely on the events of the game but were based on previously constructed knowledge that helped determine where and when players should be positioned on the field in the unfolding game. Participants specified that some settings in the game offered opportunities to act with respect for sequences of actions that were routinised within the team. For this reason, they acted based on their knowledge constructed as a football player. Informational resources relying on this theme included the following typical underlying first-order themes: expecting opponents' movements, as inferred through the use of generic football-game knowledge, and expecting teammates' movements, as inferred from teamwork knowledge (see Table 2). The following excerpts from the self-confrontation interviews illustrate this theme, including the related behavioural description:

'The game is far away from me. I'm not concerned about the game, but I know that in case we lose the ball, I have to be ready. Thus, I'm just focusing on coming back to my position to defend.' (D1/17/261/6.1) [The team is on the attack; one team member attacker just received the ball. D1 is far away from the game.]

'I know that when the configuration goes like this, A10 will move towards the ball carrier. We worked on this specific situation during training, so I just adapt my behaviour according to the tactic that we learned. When this the ball carrier is there, A10 has to come and I have to go back.' (M7/24/20/6.2) [The team is on defence; an opponent midfielder just received the ball on the right side before the middle line. A10 is going to run towards the ball carrier.]

Table 2
Frequency and intraclass percentage of SIRs used by the team members during a match.

Informational resources supporting participants' activities	D1		D2		D3		D4		M5		M6		M7		A8		A9		A10		Total
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	% (SD)
1-Informational resources relying on a single player, as captured from a focalised perception (T1)	**15**	**25.01**	**22**	**34.91**	**28**	**41.79**	**25**	**43.87**	**26**	**37.68**	**31**	**46.97**	**25**	**36.76**	**27**	**46.55**	**24**	**34.92**	**20**	**39.22**	**38.77 (6.56)**
1.1 Focusing on the attitudes of a ball carrier teammate	7	11.67	11	17.46	8	11.94	3	5.26	10	14.49	11	16.67	10	14.71	7	12.07	6	9.52	9	17.65	13.14 (3.88)
1.2 Focusing on the attitudes of a ball carrier opponent	1	1.67	0	0.00	7	10.45	2	3.51	1	1.45	3	4.55	2	2.94	3	5.17	0	0.00	1	1.96	3.17 (3.09)
1.3 Focusing on the trajectory of a non-ball carrier teammate	5	8.33	7	11.11	3	4.48	6	10.53	8	11.59	4	6.06	7	10.29	10	17.24	4	6.35	1	1.896	8.79 (4.33)
1.4 Focusing on the trajectory of a non-ball carrier opponent	1	1.67	2	3.17	4	5.97	8	14.04	6	8.70	4	6.06	2	2.94	5	8.62	14	19.05	3	5.88	7.61 (5.37)
1.5 Focusing on the inter-personal distance separated the given player from another team member	1	1.67	2	3.17	6	8.96	6	10.53	1	1.45	9	13.64	4	5.88	2	3.45	0	0.00	6	11.76	6.05 (4.84)
2-Informational resources relying on a spatiotemporal shape, as captured from a bird's-eye viewpoint (T2)	**14**	**23.34**	**8**	**12.70**	**10**	**14.93**	**10**	**17.55**	**15**	**20.30**	**12**	**18.19**	**12**	**17.64**	**8**	**13.79**	**8**	**12.70**	**12**	**23.52**	**17.47 (4.02)**
2.1 Perceiving spatiotemporal state of the team	7	11.67	1	1.59	3	4.48	1	1.75	5	7.25	2	3.03	3	4.41	0	0.00	1	1.59	4	7.84	4.36 (3.60)
2.2 Perceiving a small collective unit (e.g. defenders, attackers)	4	6.67	5	7.94	3	4.48	6	10.54	5	7.25	6	9.09	6	8.82	3	5.17	6	9.52	2	3.92	7.34 (2.25)
2.3 Perceiving a free area that affords a possibility of action	2	3.33	2	3.17	3	4.48	1	1.75	3	2.90	3	4.55	0	0.00	4	6.90	1	1.59	5	9.80	3.85 (2.82)
2.4 Perceiving a high density of players in a given area of the field	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	1.52	0	0.00	1	1.72	0	0.00	1	1.96	0.52 (0.84)
2.5 Perceiving the configuration of the instantaneous power balance between both teams	1	1.67	0	0.00	1	1.49	2	3.51	2	2.90	0	0.00	3	4.41	0	0.00	0	0.00	0	0.00	1.40 (1.69)
3-Informational resources relying single player associated with a spatiotemporal shape, as captured by a perceptual sharing (T3)	**7**	**11.67**	**14**	**22.22**	**15**	**22.40**	**13**	**22.80**	**14**	**20.30**	**6**	**9.09**	**5**	**7.35**	**9**	**15.51**	**13**	**20.62**	**5**	**9.80**	**16.18 (6.19)**
3.1 Simultaneous perception of a many players' movements and focalisation on the attitudes of a single player	2	3.33	1	1.59	2	2.99	0	0.00	1	1.45	2	3.03	0	0.00	1	1.72	1	1.59	1	1.96	1.77 (1.15)
3.2 Simultaneous perception of the ball carrier with and the spatiotemporal state of a small social unit	1	1.67	4	6.35	4	5.97	5	8.77	5	7.25	2	3.03	2	2.94	0	0.00	4	6,35	0	0.00	4.23 (3.11)
3.3 Simultaneous perception of the behaviour of a given agent and the current area where the play is unfolding	4	6.67	7	11.11	6	8.96	3	5.26	3	4.35	2	3.03	2	2.94	6	10.34	5	7.94	2	3.92	6.45 (3.01)
3.4 Simultaneous perception of a given player and one or more other players located in a very distinct area of the field	0	0.00	2	3.17	3	4.48	5	8.77	5	7.25	0	0.00	1	1.47	2	3.45	3	4.74	2	3.92	3.73 (2.84)
4-Informational resources relying on the ball area where current play is unfolding, as captured from a relocated focalisation (T4)	**16**	**26.65**	**9**	**14.29**	**6**	**8.95**	**5**	**8.77**	**6**	**8.70**	**11**	**16.67**	**19**	**27.96**	**10**	**17.24**	**10**	**15.88**	**8**	**15.69**	**16.08 (6.80)**
4.1 Focusing on the trajectory and movement of the ball	5	8.33	3	4.77	1	1.49	0	0.00	0	0.00	0	0.00	7	10.29	5	8.62	1	1.59	3	5.89	4.10 (4.00)
4.2 Focusing on the players' behaviours around the ball	11	18.32	6	9.52	5	7.46	5	8.77	6	8.70	11	16.67	12	17.67	5	8.62	9	14.29	5	9.80	11.98 (4.26)
5-Informational resource relying on proximal surrounding behaviours, as captured from a comprehensive awareness (T5)	**3**	**5.00**	**5**	**7.94**	**3**	**4.48**	**3**	**5.26**	**7**	**10.14**	**2**	**3.03**	**5**	**7.35**	**1**	**1.75**	**6**	**9.52**	**2**	**3.92**	**5.84 (2.79)**
5.1 A broad and non-directed perception of what happens near to the player (e.g. ball, player, space, interpersonal distance)	3	5.00	5	7.94	3	4.48	3	5.26	7	10.14	2	3.03	5	7.35	1	1.75	6	9.52	2	3.92	5.84 (2.79)
6-Informational resources relying on previously built knowledge suggesting an event expected to happen (T6)	**5**	**8.33**	**5**	**7.94**	**5**	**7.44**	**1**	**1.75**	**2**	**2.90**	**4**	**6.06**	**2**	**2.94**	**3**	**5.17**	**4**	**6.35**	**4**	**7.84**	**5.67 (2.39)**
6.1 Expecting opponents' movements, as inferred through the use of generic football-game knowledge	3	5.00	3	6.35	2	2.97	0	0.00	2	2.90	3	4.55	1	1.47	3	5.17	2	3.17	4	7.84	3.94 (2.30)
6.2 Expecting teammates' movements, as inferred from teamwork knowledge	2	3.33	2	1.59	3	4.47	1	1.75	0	0.00	1	1.52	1	1.47	0	0.00	2	3.18	0	0.00	1.73 (1.50)

4. Discussion

As a starting point, we presumed that understanding team effectiveness in naturalistic sport settings should benefit from an investigation of how teamwork is dynamically achieved in real time. Our study particularly focused on the content of informational resources supporting football players' real-time spatiotemporal adjustments on the field. We assumed that such informational resources were usually presupposed in the theoretical background of existing studies rather than empirically described. Our bias was to focalise on the way space-time team coordination needs were enacted by the participants. In this light, the present study aimed at providing an open account of the spatiotemporal content of the informational resources that supported team members' activities when they contributed to the collective behaviour. The results of the present study revealed the spectrum of informational resources supporting the team members' meaningful spatiotemporal adjustments, highlighting the relative divergence between three main informational resources: one accounting for local information, a second for global pictures of the game, and a third related to previously built knowledge.

Regarding local informational resources, we found that players' activities could be supported by a single player, as captured from a focalised perception (T1), and by the ball area where the current play is unfolding, as captured from a relocated focalisation (T4). Both accounted for a perception that was focused (i.e., on a given player and/or ball). Local informational resources also reflected instances of comprehensive awareness of the nearby space, as when players tried to be attuned to all proximal surrounding behaviours (T5). Together, these aspects (and the related informational resources) were considered local because they did not require players to grasp any configuration of play or multiplayer structure. In related activities, given team members behaved based on being attuned to other players' attitudes, the trajectory of the ball and/or player(s), or to any interpersonal distance.

As observed in other instances, the players were also able to grasp some global configurations of play, as when perceiving multiplayers' spatiotemporal shape (T2). In related activities, team members behaved based on being attuned to the spatiotemporal configuration of a given unit of players (i.e., defenders, attackers, or the whole team) or to a perception of a given space (e.g., free space), as allowed by grasping the dynamics of the game from a bird's eye viewpoint. Participants remained particularly sensitive to the density of players (i.e., low or high) in a space. For Example, players attempted to move where the density was low or attempted to avoid overcrowding an area and thus maintain low density in the space.

Interestingly, two remaining themes (T3 and T6) resist falling exclusively into local or global categories of informational resources. The first (T3) was described as being allowed by the perceptual sharing achieved by a given player and was characterised by the perception of a single player's behaviour on one side and a spatiotemporal shape on the other side. It was neither local nor global but combined both types of resources. The second (T6) was very specific and did not fall into a continuum of local/global resources. This informational resource was identified as accounting for previously built knowledge suggesting an expected event. We considered it inappropriate to discuss this 'knowledge-based' resource in the same way as other informational resources that were all situational. This theme accounted for a team member's activity regulated according to virtual expectations generated by the players based on their previous football experience, allowing them to anticipate probable event(s) without the need to check real current events (Blickensderfer, Reynolds, Salas, & Cannon-Bowers, 2010). We now discuss the results in light of how they relate to previous literature.

4.1. Reiterated evidence of informational resources relying on a local level of organisation

First, the informational resources identified as relying on a comprehensive awareness of proximal surrounding behaviours implied that a given player aimed at being sensitive to all neighbouring events that he was able to grasp (T5). In such cases, players exhibited a radar-like awareness (i.e., sweeping perception of the nearby environment), waiting for any local event to become meaningful and support how they regulate their behaviour. Such awareness was referred to as a local way of regulating individual contributions to collective behaviour. Such broad attentional readiness has already been suggested in sport science literature (Silva et al., 2013, 2014), especially within the ecological dynamics approach in which an individual's capacity to regulate behaviour is assumed to be supported by the perception of affordances (Passos, Araújo, & Davids, 2016). The concept of affordances refers to the possibilities of action that emerge from the interactions of an organism within a physical or social environment (Gibson, 1979). When a 'possibility for action' is suddenly offered, this appears to the player to be a meaningful solution.

However, in the theory, affordances are viewed as emerging from a direct perception of the performance's physical environment. In our theoretical and methodological design, we considered the players' subjective own world as a preliminary condition of describing the affordance. In this light, while described in the present study using a quite divergent theoretical background, the empirical description of what it means to be attuned through a radar-like awareness, as observed in our data, fits well with the requirement of a perceptual readiness, as conveyed in affordance-based studies (Rietveld et al., 2016). Our participants tried to maintain an open perceptual readiness, waiting for a chance for action to become meaningful. In this way of enacting their world, players did not focalise on a specific variable, such as interpersonal distance or players' velocities, thus illustrating how local coupling to others can be achieved while not monitoring predetermined informational resources assumed to reveal expected opportunities for action. Considering that an important difference exists in terms of perceptual attitudes between being focalised on a given behavioural variable (e.g., a given player's trajectory or a given interval) and staying aware of the behavioural events that one can grasp in a nearby space (i.e., a radar-like readiness), it is noteworthy that most studies on social affordances are not clear on this distinction. While affordance theorists have described such a goalless and undirected awareness in animal species, studies conducted in sport with respect to the ecological dynamics approach have suggested that players (e.g., a rugby ball carrier) can improve their behavioural regulation by becoming attuned (i.e., focalised) to very specific spatiotemporal information, such as interplayer distance variability (Passos et al., 2011). In light of the identified theme as discussed here (T5), our results show that football players were able to deliberately disregard the nature of information that would make possibilities for action appear, thus keeping all options available.

Second, another theme observed in the present study matches with existing sport science research: the theme referring to cases of informational resources relying on a single player (T1), where the given player focused on a specific behavioural variable. The given variable might be captured from the player's attitudes, movement, trajectory, or interpersonal distance to another team member. Such an empirical observation thus corroborates existing studies that suggest interpersonal distance variability (Passos et al., 2011), players' velocity (Passos et al., 2008), or attacker–defender angles (Araújo et al., 2006) as good candidates to support part of the affordances in team sport. This implies that some of the players' spatiotemporal adjustments, as observed on the field, were achieved by disregarding the capturing of shapes, lines, or configurations of play, thus fitting well with local coupling to other players (i.e., mainly nearby players).

This local coupling process is in line with previous work in the ethology literature describing swarming behaviours, which has inspired sports science (Silva et al., 2014). While difficult to strictly apply to team sport, paradigmatic examples have come from the knowledge base relating to the collective behaviour of schools of fish (Couzin, Krause, James, Ruxton, & Franks, 2002; Gautrais, Jost, & Theraulaz, 2008), whereby each fish only needs to follow simple interaction rules such as collision avoidance and maintaining interagent velocity. Our results again illustrate how a local coupling process may develop on the field of naturalistic football, disregarding how teamwork emerges at the team level. Interestingly, this mode was predominant in our dataset, thus confirming the relative relevance of affordance-based descriptions of collective behaviour in sport, mainly grounded on this assumption. However, and together with the results discussed in the previous stage, our study suggests that future research should better distinguish between the underlying perceptual readiness involved, such as between being focused (i.e., focalising) and staying aware (i.e., with a radar-like involvement). The process of constructing expertise in contributing to team behaviour should probably include training practices and mental preparation that alternate between both kinds of perceptual readiness, because both would probably not be governed by similar mental skills.

Third, the theme describing informational resources as relying on the ball area where the current play is unfolding (T4) considered that players regulate their own behaviour via a geographically transferred awareness (i.e., towards the ball area), sometimes located far from the given player's nearby space. In this case, players' activities were viewed as again supported by local informational resources even when resources were outside the surrounding space. For a given player, this way of regulating his interacting activity invites researchers to be cautious when assimilating the notion of perceptual focalisation with that of nearby space awareness. Interestingly, when one considers that many players can simultaneously monitor the ball area while not adjusting their respective behaviours through direct coregulation between themselves, the resulting collective behaviour should be described as an indirect mode of coordination (Gesbert, Durny, & Hauw, 2017). As previously evidenced in basketball (Bourbousson, R'Kiouak, & Eccles, 2015), convergent/coordinated behaviours of team members can be achieved by sharing similar informational resources, without each player necessarily taking his teammates into account. R'Kiouak, Saury, Durand, and Bourbousson (2018) recently elaborated on the fundamentals of such a process in their stigmergic view of teamwork. In their study of a rowing setting, team members exhibited highly synchronised patterns of collective behaviour, achieved not by direct co-awareness of their behaviours but by exhibiting individual activities that were supported by a simultaneous awareness of their shared environment (i.e., the boat in the study setting). Such a stigmergic mode of coordination was also investigated and called an extrapersonal coordination process (Millar, Oldham, & Renshaw, 2013). This stigmergic process can be an effective innate way of making collective behaviour emerge and of preserving multiplayers' coupling with key environmental events, such as those occurring in the ball area in the present football study setting.

Finally, informational resources relying on previously built knowledge suggesting events expected to happen (T6) have been mentioned in previous research. In this light, the social-cognitive perspective of team coordination (Eccles & Tenenbaum, 2004) assumes that patterned teamwork mainly arises through sharing knowledge within the team, which refers to similar representations of the task and the team routines across team members. According to this approach, shared knowledge helps team members form clear expectations about others' actions so that situational probabilities (as conceived in the head of the player) can support the way each teammate behaves, rendering real-time event monitoring and related cognitive interpretation not always necessary (e.g., as in performing a no-look pass). Such a team coordination process has been called implicit and has been assumed to be highly knowledge dependent (Blickensderfer et al., 2010). The knowledge that each team member can mobilise in the game is available so that he or she is still capable of adjusting the activity based on expectations even if he or she does not necessarily grasp the current state of the game (i.e., probabilistic events rather than situated informational resources). However, while sociocognitive theory postulates that most team coordination arises this way in expert teams, informational resources relying on previously built knowledge were far from being prevalent in our data.

Several studies have already suggested that knowledge-based coordination is scarce in the unfolding of teamwork in real time in sport, probably due to the difficulty of having coordinated mental states in a team that can represent all possible events of a game. For instance, the elements of knowledge mobilised by team members in basketball have been found to be rarely shared among team members (Bourbousson et al., 2011), as were their game-related concerns and the related shared understanding (Bourbousson et al., 2012). Our results provide further evidence that prompts researchers to reexamine the assumption that the sharedness of cognitive content could be the key condition to achieving viable team coordination (Araújo et al., 2006; Bourbousson et al., 2012).

4.2. Importance of informational resources relying on a global level of organisation

When players' activities were supported by informational resources relying on a spatiotemporal shape (T2) within the game, the players perceived the game events as if they were capable of a bird's eye viewpoint. This led them to build either a global perception of their own team behaviour (e.g., positioning of defensive and offensive lines) or a perception of the density of players within some areas on the field (i.e., looking for free space). Surprisingly, the research on collective behaviour has overlooked the capability of human team members to grasp in real time the global picture that they help develop (see Bourbousson & Fortes-Bourbousson, 2016). The only proposal we found in the literature was by Grehaigne et al. (2011), but such a perception of the configuration of play was mainly presupposed rather than empirically documented. Another insight comes from a game analysis study that showed how individual behaviour in team sports can be more constrained by collective behavioural variables than by local ones. Basketball players' dribbling to the basket (i.e., driving) was shown to be supported by a disruption of the relationship between the centres of opposing teams and between their stretch indexes rather than being supported by the events occurring in the attacker–defender dyad (Grehaigne et al., 2011).

The findings of these studies are in line with the present observations that suggest players can have a sense of the dynamics of global behaviour. It is important to consider that, unlike in the animal world, human collective behaviour itself can support co-interactors' adaptive activity and thus be considered a nonnegligible informational resource. Such an ability to grasp the overall emergent states achieved through teamwork has been called *holoptism* (Bourbousson & Fortes-Bourbousson, 2016; Noubel, 2004). Holoptism occurs when any team member grasps the dynamics of the whole interactive system and behaves in light of the given real-time joint effort perceived. To date, while being especially relevant to human behaviours, holoptism has not been investigated in sport. It must not be confounded with the perception of every team member's behaviour implied in the social system, which does not require a bird's eye viewpoint. To illustrate, a recent study on people dancing in a social situation showed how participants could perform feats while being aware of the movement of every other participant and while moving on a very large dance floor (Long, Jacob, Davis, & Magerko, 2017). Thus, holoptism, as suggested in the present study, accounts for a distinct sensibility phenomenon of being aware of the individual motions of every player on the team (Long et al., 2017). In other words, one should not confuse exhaustive local couplings with adapting one's behaviour vis-à-vis the global dynamics of the social system as a whole. Empirical evidence of holoptism in human movement science has recently been found in the literature (Bourbousson & Fortes-Bourbousson, 2016), and our present study supports this evidence.

In addition, the informational resources relying on the simultaneous consideration of a single player and a spatiotemporal shape (T3) suggest that players can also mix global and local resources, as when being attuned to different simultaneous and distinct targets. The activity of players was here experienced as the hard task of sharing attention by monitoring two concomitant informational resources of diverging nature. Interestingly, in addition to showing that local and global modes of regulation were time chained together in the dynamics of the game, our results also show how global perceptions did not exclude local ones when considering a single instant. From an intuitive standpoint, such a combination of local and global informational resources can represent a powerful mode of perception, making both informational resources work together to build the experiential picture from which the player makes decisions. In such a case, the team member was simultaneously able to ensure the relevance of his activity in the vicinity by managing local couplings (e.g., monitoring his nearby space) and to update/challenge how he behaved locally by monitoring states of effective teamwork patterns.

5. Implications and conclusions

In terms of theoretical considerations, our enactivist approach to teamwork illustrates how research can go beyond analytic paradigms using a unified activity-centred framework. In this way, our phenomenological prism was able to provide an empirical description that did not confine informational resources to any presupposed content. The present study could therefore serve to challenge existing studies and their assumptions about how team members coordinate in real time. In this light, our study proposes that teammates' active regulation of their behaviours was not predominantly knowledge based but rather embedded in situational opportunities for action, while these opportunities could not be reduced to local-level affordances. Considering the actors' phenomenology thus helped to propose a modelling free from bias regarding the content of informational resources supporting spatiotemporal adjustments.

In terms of practical considerations, our study provides coaches with new knowledge about informational resources mobilised by football players when adjusting their displacement on the field, regarding the spatiotemporal needs they perceive online. In light of the global mode of regulation exemplified here, coaches could develop practices offering spacing large enough so that the density of players becomes salient (i.e., free space and densified space) and call players to use the global perception of team states. To complement this training approach, coaches could develop practices using small-sided games, implying short interplayer distance and time pressure, which are supposed to call for local awareness development. In terms of mental training, practitioners could invent exercises to help players make a switch in mental attitudes and perception (e.g., from broad unfocused to directed awareness and from local to global awareness).

Moreover, one probable area for the technical application of our study results would be multi-agent system simulation. Most of the current collective behaviour simulation has been inspired by simple local rules of interaction suggested in ethology research. Promising research projects could be built that investigate the benefits/disadvantages of distinct modes of regulating individual agents' contributions to teamwork, as do some projects based on monitoring team states.

While our study has its strengths (e.g., a large number of players and a real-world investigation respectful of agents' phenomenology), it also has its limitations. First, in terms of the external validity of the findings, the study involved a relatively small dataset with only 10 players from one individual team and a small game time sampled (10 min). Future studies should involve larger samples of teams and data representing larger portions of games. The desire to ground activity regulation in the meaning placed on events by participants and in the natural team context meant that the method adopted was time-consuming. Moreover, the team was relatively skilful; future research should involve teams at different skill levels. Second, in terms of internal validity, the data were based on participants' verbal reports about their activity, as collected during self-confrontation interviews. Such verbal reports were obtained through the actor while he watched himself involved in the game on a TV screen. This could have influenced the nature of his verbalisation, especially by making him report mostly visual perceptive activity. Thus, future research must challenge our results by using other data collection methods so that a deeper account of the players' phenomenology could be provided. In the present study, the results mainly accounted for visual perceptions and intentions, probably missing body-based sensitivity components that support how players' active and meaningful regulation of their displacement occur on one side, and probably minimizing the role of overt and explicit interpersonal communication on the other side.

In terms of the study object, future research should offer an explanation about the extent to which similar modes of regulation must (or must not) be shared within the team or exhibit a distribution of the informational resources used at the scale of the team. Our study also did not address the knowledge related to the conditions of occurrence and/or effectiveness of the different regulation modes observed here. Finally, future research should investigate how various levels of practice correlate with distinct players' perceptual readiness and/or how the use of a given informational resource can be learned through practice.

To clarify the contribution of this research, while the empirical evidence provided supports the local coupling process as the most prevalent way of interacting with others in an ongoing joint effort, as hypothesised by Passos et al. (2008, 2011), a nonnegligible amount of global informational resources has been pointed out in the present study, suggesting holoptism as a plausible competing underlying process of teamwork.

To conclude, the aim of our study was to provide observations about the diversity of informational resources that can support players' activity when involved in spatiotemporal teamwork, about how informational resources were chained together in the unfolding activity of a given player, and about how they were distributed across participating players. Our study described a part of the complexity of regulating individual activity when contributing to teamwork. Such regulation was mainly based on local and global informational resources, including the simultaneous co-occurrences of these resources and their divergence from knowledge-based modes of regulation. Alternating between focalised perceptions and open awareness and between nearby space and distant perceptions, players' activities were supported by diverse informational resources that were far more important than the ones assumed in each of the frameworks available in the literature. This diversity should thus call into question the ecological dynamics framework, which presupposes the local nature of regulation implied in human activity and makes this approach mainly unable to consider regulation modes that are distinct from local ones. The social-cognitive approach should also offer explanations of how situational resources can be so prevalent in real-time team coordination in comparison to the knowledge-based resources it assumes.

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STUDY 2 - A SIMULATION STUDY OF INDIVIDUAL ADJUSTMENT IN FOOTBALL

Introduction. Our project aimed at improving the understanding of dynamical collective behaviour by providing insights into how players adjust their personal contribution to the team behaviour at every moment. A previous study has shown that players use different adjustments (Feigean et al., 2018). Two primary adjustments were described: local when players interact with only a single other player and global when players interact with the global spatiotemporal shape. The purpose here was to test hypotheses about local and global adjustment modalities at the level of team behaviour. We conducted a simulation study of football to provide insight into how changes in players' individual adjustments give rise to distinct correlates in the simultaneous team behaviour.

Method. We created a dynamical model of two interacting football teams, which was built accounting for three physical forces that apply to every agent, called collision force, side force and zone force. We introduced local and global individual adjustment modalities, which were defined as social forces. We obtained 100 simulations. Within each simulation, individual agents' positions at each instant (i.e., coordinates) were calculated. From these data, we calculated metrics to characterize the collective behaviour, such as the centroids, the stretch index and the surface area. We looked at how such metrics varied under changes in an individual-level adjustment modality.

Results. The results showed that the centroid (*y*) was higher in terms of the direction of the game for a team configured with global individual adjustments than for a team set up with local adjustment modality. The surface area was greater for a team configured with a global adjustment modality than for a team configured with a local adjustment modality. The same result was found for the stretch index. The width and the length of the team were lower for a team configured with local adjustment modality than they were for a team configured with a global adjustment modality.

Discussion. Together, the results highlighted two specific behaviours, a condensed behaviour that was obtained via the local adjustment modality and a deployed behaviour obtained from the global adjustment modality. This study suggested new directions for research on teamwork in sport teams. The simulation device adopted here also provided the opportunity to generate a large amount of spatiotemporal data that are hard to capture in a natural sport setting.

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Alternative modalities of individual adjustment and their correlates in terms of collective behaviour emergence

A simulation study in football

Mathieu Feigean · Guillaume Grégoire · Quentin Clément · Roland Seiler · Jérome Bourbousson.

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Abstract Our project aimed at improving the understanding of how a space-time collective behaviour dynamically emerge from individuals' adaptions. The present simulation study in football contributes to this aim by providing insights into how changes in the players' individual adjustment at every moment gives rise to distinct correlates in terms of the simultaneous team behaviour. As a preliminary requirement, we created a minimalist dynamical model of two interacting multi-agents systems reflecting a football teams contest.This model was based on elementary football rules and three implemented physical forces that apply to each agent at every moment, called avoidance-, side-, and zone-forces. From this model, we built additive forces related to individual agents' adjustments to others' displacements, called social-forces and related either to local or global space-time ongoing adjustment modality, respectively. 100 simulations were generated in which individual agents' position at each instant (*i.e.*, x, y coordinates) were obtained. From these data, we calculated metrics to capture the collective behaviour of a given team, such as the team centroid, stretch index and surface area. We then scrutinized how such metrics correlated with changes in individual-level adjustment modality. The results showed for instance, that the surface area was higher when agents' adjustment was set to global, as was the the stretch index. Together, the results suggested two distinct collective behaviour properties, that were a condensed and a deployed behaviour, respectively; the former is composed of agents interacting through local adjustment and the latter is rather correlating individual global adjustment modality. Based on technics used in physics, the present study gives new directions for the research on teamwork in sport teams. Future projects could test a large panel of teamwork-related hypotheses using simulation tools.

Keywords Football simulation · Collective behaviour · Adjustment

Mathieu Feigean
Bremgartenstrasse 145,3012, Bern
Tel.: +41.78.605.82.36
E-mail: mathieu.feigean@orange.fr

1 Introduction

In the last decade, many team sports (especially football) have been studied to understand how collective behaviour emerges, changes, and is recovered [3,6,19,25,8,32]. The science of football has focused on team architecture that changes over time in terms of the team center, team dispersion and team synchrony [2]. Following these characteristics, a team is assumed to behave as a single coherent unit. From this perspective, team behaviour is seen as emerging from the many a players' interactions in an ongoing situation, illustrating that small changes to individual behaviour adjustment lead to significant effects in team properties and organization [28,11]. Bourbousson & Fortes-Bourbousson [5] stated that the understanding of team properties would benefit from investigating the level of agents' regulation, which includes changes in individual adjustment modalities. Individual adjustment can be defined as the way individual agents consider their own world and maintain or change trajectories accordingly in a specific time. The present research aimed to determine and test hypotheses about how individual adjustment modality changes were reflected at the collective behaviour level.

Grounded on dynamical systems theory and the principles of ecological psychology, ecological dynamics framework has emerged as a powerful theoretical approach to uncover the laws that regulate the team behaviour [1,33,35]. Teamwork (i.e., the interpersonal interaction process leading to team behaviour) occurs as a self-maintained process. Team structure emerges from the adjustments between the players and exhibits the signatures of a self-organized system. Understanding team behaviour, thus, relates to the investigation of how real-time interactions between teammates and opponents occur in space and time during the emergence of play patterns at different levels [34]. However, ecological dynamics theory has assumed that collective behaviour could be investigated in terms of its own dynamics, disregarding how interactions are linked to individuals' internal cognitive processes. For instance, studies conducted with this approach have developed tools capable of capturing team properties, notably by elaborating on team metrics, such as the centroid position, the stretch index or the surface area of the team [15]. In line with dynamical systems principles, such team metrics have been considered *order parameters*, while significant local constraints observable at a more microscopic level of description were designated *control parameters*. A control parameter is defined as a variable susceptible to modifying the essentials of team behaviour (i.e., the order parameters) when the variable value evolves beyond a critical value [13]. Previous research based on the dynamical systems approach to team sport has focused primarily on how some metrics, such as surface area, can serve as parsimonious macroscopic descriptors of what happens in the social system [16,26,29]. However, said research neglected to provide a clear description of how the microscopic level of the system is implied in the self-organised behaviour [5]. In other words, previous researchers, following ecological dynamics theory, adopted a prism that overlooked the way individual interactors in the system manage their own space-time interactions. However, when one considers humans to be uncertain interactors that are not determined solely by external factors, are able to exhibit their own very distinct worlds (i.e., they have subjective perception and experience their own phenomenological world in which they pursue their own intentions) and are free to change their interaction modalities while disregarding observable environmental reason [14], a research gap remains when describing how individual interactor perspectives influence team behaviour.

As in other collective systems, team sport player expertise relies on decision-making qualities regarding movement timing and location for adapting to dynamical environmental conditions [12]. Through practice, players refine their actions by adjusting their individual space-time behaviour functionally to those of their teammates and opponents [18]. When a given player interacts actively with others during a game, various informational resources support adjustments [19], the nature of which is subject of persisting scientific debate. In a previous study, Feigean et al. [19] described a landscape of potential informational resources appropriate for describing what supports adjustments in space-time and movement of individual team sport players. These informational resources were either purely local (e.g., interacting with a single player) or tapped into global resources (e.g., grasping the space-time shape formed by a player's own team). Players' interactive activity alternatively grounded on

1. a single player, as captured from a focalised perception;
2. a global space-time shape, as captured from a bird's-eye viewpoint;
3. a single player associated with a global space-time shape, as achieved through a perceptual sharing;
4. a ball area where a current play was unfolding, as captured from a distant relocated focalisation;
5. surrounding behaviours, as captured from a comprehensive awareness of the nearby space (when players attempted attunement with all proximal surrounding events); and
6. previously-built knowledge suggesting an expected event was about to happen.

Amongst these informational resources, modalities 1 and 4 were considered local resources supporting adjustments. As highlighted by other adjustment modalities, such as modality 2, players were also able to grasp some global configurations of play, such as perceiving a multiplayer space-time shape where players were shown to be attuned to the space-time configuration of a given unit of players (e.g., defenders, attackers, or a whole team) or to a perception of a given space (e.g., free or dense space).

The present study aimed at exploring how changes in individual adjustment modalities correlated with distinct significant consequences at the level of collective behaviour, as captured through simulated team metrics. Inspired by the study of Feigean et al. [19], we adopted a perspective that differentiated between local and global individual informational resources supporting the individual adjustment modalities. Such a dichotomy was suggested in many fields of research. Theoretical physics studies have shown that purely local interaction [21], a closed neighbourhood on a network [20], and a globally coupled population lead to very different collective behaviours. In ethology, Perna et al. (2011) discovered purely local mechanisms have been exhibited in termite nests, involving the arrangement of simple structures according to predetermined rules of behaviour. By contrast, the estimation of global properties (described as the densities, concentrations and traffic of the termites) has also been illustrated [27]. In robotics, adjustment modalities have been considered able to create collective robot behaviour [24]. In the field of the sensori-motor synchronization between humans, research has shown the human capability to grasp the global time structure of an interactor's movement when involved in achieving a collective behaviour in real time [23]. With a specific interest in the football description, the present study aspires to make a wider contribution to this topic, transverse to the study of complex social systems.

To test the effects of different adjustment modalities, our project needed a simulation model of the space-time collective behaviour for a multi-agent system (MAS). The MAS was built to reflect the essentials inherent in the complex social systems of football team behaviours. We expected to demonstrate the dynamical patterns of collective behaviour dependent on the adaptive adjustment modalities implemented in the behaviours of the individual agents comprising the MAS. We constructed a football model that exhibits collective team behaviour, which led us to consider our model realistic in terms of its space-time view. This model was composed of physical and social forces. Following a logic parallel to Feigean et al. (2018), our study attempted to transcribe individual adjustments in terms of social forces to construct the model. Physical forces reflected environmental constraints (e.g., staying in the field, moving towards the goal) and tactical constraints (e.g., achieving a team consistency and space occupation that maintained game balance, avoiding off-side). Using these definitions, physical forces were synthetized in a collision force and a side force. Then, social forces reflected the local and global adjustment modalities, mathematical rules were then synthetized respectively. Two terms described individual, the term of agent was related to the study and the model whereas the term of player was related to the football game.

This study explored how changes in individual adjustment modalities can be associated with significant changes in collective behaviour, as observed through team-metrics values. We expected that metrics about the dispersion, the centroid, and the surface area of the team allowed for the capturing of such changes. It was also expected that changes in the metrics occurred while observing a certain consistency of the simulated game balance, thus maintaining the realistic property of the football match. Since Feigean et al. [19] showed that the density of spaces was a key point of game organization, we expected the team metrics to vary across simulation conditions, suggesting that collective behaviour has changed in terms of density. Our study design was thus expected to provide evidence that individual adjustment activity was a non-negligible aspect of complex social system patterning.

2 Model

The social force model [22, 7] we used assumes that pedestrians are active mechanical objects; their behaviours can be described by classical Newtonian laws and by forces. Their motions appear because there is a desired velocity v_d that each individual aims to achieve. As a result, agents are propelled by a force which depends on v_d. That being said, frictions also limit their velocities and the balance of these two terms acts as a saturation term. We wrote this term as Stokes' friction law, the simplest available law.

The model computes the mental process of agent through a Langevin-type equation [7] where there are external influences or forces, an inner latency with a time τ_d, a mental inertia m_m and a Gaussian noise η which models stress or confusion with an effective diffusion coefficient D. The resulting equations are:

$$m\frac{d\mathbf{v}}{dt} = \sum \mathbf{F}_{\text{physical}} + \frac{m}{\tau}(\mathbf{v_d} - \mathbf{v}) \tag{1}$$

$$m_m\frac{d\mathbf{v_d}}{dt} = \sum \mathbf{F}_{\text{social}} - \frac{m_m}{\tau_d}\mathbf{v_d} + \frac{m_m}{\tau_d}\sqrt{\frac{2D}{\tau_d}}\eta \tag{2}$$

In this model, agents move according to three different constraints:

1. *the physical forces* including the avoidance of contact and any relation with the environment, such as the limitations of the field;
2. *the fooball rules*, such as off-side rules; and
3. *the social forces*, which take into account the agents' interpersonal coordination (i.e., their willingness to perform as a football team).

2.1 Geometry

Agents move on a field of width ℓ_x, and length ℓ_y. The coordinate axes are called x and y, as usual. The vectors are indicated in bold. Thus, the unitary axes vectors are $\mathbf{e}_x$ and $\mathbf{e}_y$. Positions are called $\mathbf{r}$, and agents are labelled by integer i. The origin of the frame is fixed at the center of the field.

2.2 Physical forces

Physical forces describe the fact that each agent is constrained by environmental rules without any delay in any mental process. In the model, two forces are considered physical: the collision force and the side force.

Collision force forbids two agents i and j to be at the same location (x,y). This force describes spatial occupation by a single agent and the avoidance radius r_c is the width of an agent. Its potential diverges when the distance between the two agents vanishes, so the force is:

$$\mathbf{F_C}(\mathbf{r}) = \begin{cases} 2U_c\left(\frac{r_c}{r^2}\right)^2 \mathbf{r}, & \text{if } r < r_0 \\ 0, & \text{anywhere else,} \end{cases} \tag{3}$$

where $\mathbf{r} = \mathbf{r_i} - \mathbf{r_j}$, with $\mathbf{r_i}$ being the position of agent i, U_c is the norm of the potential and r_c is the avoidance radius of an agent. In our model, the collision force is only considered when the distance of two agents is less than parameter r_0.

Side force is a constant equal to F_B when an agent moves off the field. The side force describes the way agents try to stay on the field and the way they try to return to the field:

$$\mathbf{F_B}(x_i,y_i) = \begin{cases} F_B\,\mathbf{e}_x, & \text{when } x_i < \frac{-\ell_x}{2} \\ -F_B\,\mathbf{e}_x, & \text{when } x_i > \frac{\ell_x}{2} \\ F_B\,\mathbf{e}_y, & \text{when } y_i < \frac{-\ell_y}{2} \\ -F_B\,\mathbf{e}_y, & \text{when } y_i > \frac{-\ell_x}{2} \end{cases} \tag{4}$$

where ℓ_x and ℓ_y are the respective length and width of the field.

2.3 Football rules

In this section, we explain how standard football rules are implemented in our model. We choose to describe the way the ball is managed to obtain more realistic behaviours; depending on the trajectory of the ball, agents can follow a general team lineup (e.g., how many agents are defenders), a design to pass or get the ball, or a pattern to consider the positions of teammates. These patterns are named social forces. We shall now define the implementation of the passing of the ball.

2.3.1 Pass

The ball carrier has a certain probability P of passing the ball. This probability is increased when an opponent is close to the ball carrier. The pressure of the opponent is felt from a distance D_p and decreases linearly with the distance to the defender:

$$P = max\left(\frac{dt}{T_p}, 1 - \frac{d_{ij}}{D_p}\right) \tag{5}$$

where dt is the time step, T_p is the mean time of a pass without any pressure from an opponent and d_{ij} is the distance between the ball carrier and the nearest defender.

To find a teammate to receive the ball pass, we look for one which is closest to the direction to the goal. For that purpose, we compute all angles α_i to the team members i. The angular origin is taken as the direction from the ball carrier to the goal, making it a dynamical variable. The absolute values of angles α_i are then sorted from lowest to highest.

In contrast, the risk of the pass being intercepted by an opponent decreases with the opponent's distance to the ball carrier r_j. Opponents are then sorted from the closest to the furthest from the ball carrier.

From the first team member in terms of angle to the last, we compute if a team member is able to receive the ball without interception of the opponent. To simplify our model, we assume that the pass velocity v_b is constant. Therefore, the speed v_b and the maximal displacement velocity of a agent v_0 define a certain angle α_0, with $v_0 << v_b$

$$\alpha_0 = \frac{v_0}{v_b}. \tag{6}$$

If the future ball carrier is on the axis of the cone of half-angle α_0, combined with an empty opponent cone, then the pass will arrive safely.

As we just defined a cone of interception for the future ball carrier, a new cone of interception for an opponent can also be defined. Considering all of these cones, this defines a space partitioning of forbiden zones. Then the algorithm of searching a pass direction consists of building this partitioning, and then of finding the remaining space where the ball can move without being caught by any opponent, see Fig. 1).

2.3.2 Catching the ball

Ball catching is realised by the nearest agent from the ball for each team. The trajectory of the ball is along a line and moves with a constant speed of v_b. Agents can move in any direction from their initial position $\mathbf{r}_j$, so to find the position of interception $\mathbf{r}$, one has to solve

$$\begin{cases} \mathbf{r} = \mathbf{r_b} + \mathbf{v_b}\Delta t, \\ \left(\mathbf{r} - \mathbf{r_j}\right)^2 = \left(\mathbf{v_j}\Delta t\right)^2, \end{cases} \tag{7}$$

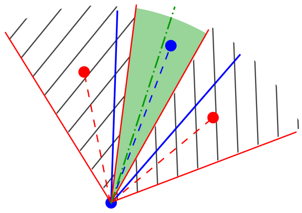

Fig. 1: Cone of possible passing towards a teammate. The green shaded zone is available for a pass. The hatched zone is unavailable for a pass, as an opponent would intercept. The dotted green line is the bisector of this zone, showing the direction the pass is made

where Δt is the time parameter. The only new assumption is that we neglect the acceleration of an agent to make the jump between $\mathbf{r}_j$ and $\mathbf{r}$ if $0 < \Delta t < dt$, letting dt be the time step. In that event, or if the ball is free, then the ball becomes kept by a new carrier. If the ball is carried, then we accept a tackle (i.e., retrieve the ball) from an opponent at a given probability.

2.3.3 Game situations

When a team gets the ball, the ball carrier is constrained to move toward the opposite goal, so we introduce a force to the goal:

$$\mathbf{F_{goal}}\left(\mathbf{r_i}\right) = \beta \cdot \frac{m}{\tau} \cdot v_0 \cdot \mathbf{e_b}\left(\mathbf{r_i}\right), \tag{8}$$

where β is a coefficient to modulate the intensity of the force, and $\mathbf{e_b}\left(\mathbf{r_i}\right)$ is the unitary vector pointing toward the goal from the agent location $\mathbf{r}_i$.

For the nearest defender to the ball, two cases can be encountered at each timestep: the ball can be carried or free. If the ball is free, a force constrains the defender to move toward the interception point and we test the condition of part 2.3.2. If a solution exists for eq. 7 and if $\Delta t \geq dt$, then the defender moves towards the ball under the action of constant force:

$$\mathbf{F_{ball}} = F_{\text{ball}}\mathbf{e_b}, \tag{9}$$

where F_{ball} is a parameter and $\mathbf{e_b}$ is the unitary vector from the agent to the ball.

If the ball is being carried, the nearest defender is forced to go to the ball carrier. To be close to reality as possible, we also include an off-side equation in the model. The equation constrains the ball carrier to not pass the ball to a teammate when that agent is off-side.

2.3.4 Zone force

Zone force considers the individual area of each agent according to their position on the field (e.g., defender, striker, midfielder). This force is derived from a harmonic potential with a center $\mathbf{r_{zi}}$ depending on the position of agent i in a specific team. In this way, an agent has a reference position on the field determined by the collective tactic (*e.g.*, 4-4-2). Futhermore, we expect that the motion of the agent $\mathbf{r_{zi}}$ is anisotropic, allowing a winger to move along the touch-line, for instance. Therefore, each agent has a prefered zone through a center $\mathbf{r_{zi}}$ and two lengths (λ_{xi} and λ_{yi}) which define the extent of the zone:

$$\mathbf{F_Z}\left(\mathbf{r_i}\right) = -2U_Z\left(\left(\frac{x_i - x_{zi}}{\lambda_{xi}}\right)\mathbf{e}_x - \left(\frac{y_i - y_{zi}}{\lambda_{yi}}\right)\mathbf{e}_y\right) \tag{10}$$

To account for the continous regulation of all the agents to the ball, the center of the zone is not fixed but changes over the time according to the trajectory of the ball. According to the length of the field, the center of the zone is calculated by adding a term to the agent position in the hyperbolic tangent of the ball position. A hyperbolic tangent function was selected to give a linear behaviour to the ball during the ball's transition phase from one part of the field to another (i.e., offensive and defensive part), and to prevent movement when the ball was near a goal. This illustrated the offensive and defensive phases, where agents were on a given part of the field, and the transition between these phases, where agents were moving from one part of the field to another one. During the defensive phase, the horizontal movement of the zone center was proportional to the movement of the ball, which relates to the actual football tactic of a team sliding when the ball moves from one wing to another. During the offensive phase, the x of the center zone was not dependent on the ball's position. The default value was simply multiplied by a coefficient η higher than 1 to spread the team around the ball.

$$\text{Offensive team}: \begin{cases} x_z = \eta \cdot x_{z0} \\ y_z = y_{z0} + \frac{\ell_y}{2}\tanh\left(\frac{2y_b}{\mu}\right) \end{cases} \tag{11}$$

$$\text{Defensive team}: \begin{cases} x_z = x_{z0} + \frac{1}{2}x_b \\ y_z = y_{z0} + \frac{\ell_y}{2}\tanh\left(\frac{2y_b}{\mu}\right), \end{cases} \tag{12}$$

where x_{z0} and y_{z0} are the default coordinates of the zone center, ℓ_y is the length of the field, x_b and y_b are the coordinates of the ball and μ is the distance from which trajectories are linear.

2.4 Social forces

Our study aims to compare two types of interactions between agents. In this section, we present these interactions as local and global regulations. A local regulation is when an agent i self-regulates behaviour by keeping a distance d_p from a specific team member j. The given team member is chosen as the nearest partner agent for i in the cone centred on i, with a half-angle $\pi/3$ and with an axis pointed on the ball. A symmetric attractive potential, whose well is approximately d_p and for which the well width is approximately δ, can be written as:

$$U = U_L \frac{-1}{\left(\frac{d_{ij}-d_p}{\delta}\right)^{2\alpha}+1}. \tag{13}$$

The derived force is then:

$$\mathbf{F_L} = U_L \frac{2\alpha}{\delta} \frac{\left(\frac{d_{ij}-d_p}{\delta}\right)^{2\alpha-1}}{\left(\left(\frac{d_{ij}-d_p}{\delta}\right)^{2\alpha}+1\right)^2}\mathbf{e_{ij}}, \tag{14}$$

where $\mathbf{e_{ij}}$ is the direction from i to j.

A global regulation is when an agent i self-regulates while taking into account all other agents j, which include both team members and opponents. To account for this, we define the interaction of a global regulation as follows: The position of each agent is defined as the center of repulsive potential. This potential is anisotropic and regular when the distance between agents is reduced. Our aim is to avoid numerical instabilities induced by divergence, but the collision force already prevents the distance being reduced to 0 (see part 2.2). The total potential, which is the sum over every agent, is stated as:

$$U = U_G \sum_{j=1, j\neq i}^{n} \frac{g_j}{\left(\frac{d_{ij}}{\delta}\right)^{2\alpha}+1}, \tag{15}$$

where n is the total number of agents, d_{ij} is the distance between agents i and j, δ is the size of the repulsive zone, α is a coefficient giving the verticality of the potential, and g_j is a coefficient weighting the importance of the opponents compared to team members. The derived force is

$$\mathbf{F_G} = -U_G \frac{2\alpha}{\delta} \sum_{j=1, j\neq i}^{n} \frac{\left(\frac{d_{ij}}{\delta}\right)^{2\alpha-1}}{\left(\left(\frac{d_{ij}}{\delta}\right)^{2\alpha}+1\right)^2}\mathbf{e_{ij}}, \tag{16}$$

where $\mathbf{e_{ij}}$ is the unitary vector pointing from agent i toward agent j.

2.5 Summary of the model and computation

Finally, the initial equations 1 and 2 become:

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \mathbf{F_C} + \mathbf{F_B} + \frac{m}{\tau}(\mathbf{v_d} - \mathbf{v}) \tag{17}$$

$$m_m\frac{\mathrm{d}\mathbf{v_d}}{\mathrm{d}t} = \mathbf{F_Z} + \mathbf{F_{goal}} + \mathbf{F_{ball}} + \mathbf{F_L} + \mathbf{F_G} - \frac{m_m}{\tau_d}\mathbf{v_d} + \frac{m_m}{\tau_d}\sqrt{\frac{2D}{\tau_d}}\eta \tag{18}$$

This system can be easily integrated due to the friction term. The damped regime makes a Euler algorithm sufficient for computing the trajectories of all team members.

2.6 Summary of parameters

A simulation of 20 agents distributed in two entities was created in a continuous two-dimensional area representing the field. The origin of the two-dimensional area was the center of the field, $(0,0)$, with the length being initialised at 120 meters and the width at 80 meters. The time was regularly partitioned into discrete time steps, dt. In this model, δt was set to 0.05 s. The following parameters were chosen by scrutinising typical football agents and games: mass, radius, velocity and ball velocity. Other parameters were not evaluated by this study. We selected the paramter value to get natural trajectories for agents. All parameters are summarized in Table 1. The model considered a desired velocity $\mathbf{v_d}$ integrated in the social forces establishment. This velocity is related to the desire an agent has to move while taking the environment into account. The model considered a characteristic time of decision making, τ_d, corresponding to the response latency of football agent, accompanied by a hypothetical mental inertia described by a mass m_m (i.e., 80 kg) using the fundamental principle of the dynamics. This model was simulated based on the initial parameters listed in Table 1.

2.7 Analysis

Throughout the simulation, we collected the positions of all agents over the scheduled time. Using positions (x,y), we calculated metrics to give an overview of the collective behaviour. Metrics were defined as geometrical measurements [9] which were used to allow for measuring the center of the team, the dispersion of the players and the expansion on the field of the team. We were always focused on the offensive team for the analysis while the defending team was always set up with no specific individual interactions.

First, we calculated the geometrical centroid (x,y) to measure the mean position of all agents. The geometrical center of a team G is defined by the equation:

$$\begin{pmatrix} x_G \\ y_G \end{pmatrix} = \frac{1}{n}\begin{pmatrix} \sum_{i=1}^n x_i \\ \sum_{i=1}^n y_i \end{pmatrix}, \tag{19}$$

where n was the numbers of agents and x_i, y_i were the coordinates of an agent i.

Second, we calculated the stretch index to measure the dispersion of agents. The stretch index is calculated as the mean distance of agents from the geometrical center, which gave the compactness of the team. The stretch index, considering both axes, at a given instant t was calculated by:

$$S_i = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i - x_G)^2 + (y_i - y_G)^2}, \tag{20}$$

where x_i, y_i were the coordinates of an agent i.

Parameter	Symbol	Unit	Value explored
Closure distance	r_0	Meters	1 to 2
Time step	Δ_t	Seconds	0.05
Radius of agent	r_c	Meters	0.3
Velocity	v_0	Meters per second	3
Coefficient velocity limit	v_{limit}	None	3
Coefficient pass velocity	v_{eps}	Meters per second	0.5
Ball velocity	v_b	Meters per second	15
Diffusion coefficient	D	None	2.0
Pass probability	P_{ass}	None	0.2
Tackle probability	T_{ackle}	None	0.2
Side potential	U_b	None	80,000
Collision potential	U_c	None	20,000
Zone potential	U_z	None	20,000
First defender avoidance	U_e	None	8,000
First defender on the ball	U_d	None	10,000
Local potential	U_{loc}	None	1,000,000
Global potential	U_{glo}	None	1,000,000
Coefficent goal	g	None	50
Size of the field	l_x & l_y	Meters	80 & 120
Initialisation of agent position	l_{dx} & l_{dy}	None	-20 to 20 & -25 to 25

Table 1: *Summary of model parameters. The use of units relates to the non-dimensionality of certain parameters in the model*

Finally, we calculated the convex hull to measure the surface area of the team. The surface area was calculated as the polygon with the lowest apex that could circumscribe all of the team's agents, and where the potential apex was given as the positions of the agents. Given a set of points, the following equation was applied to define the convex hull:

$$SA = \frac{(x_1 y_2 - x_2 y_1) + (x_2 y_3 - x_3 y_2) + ... + (x_i y_1 - x_1 y_i)}{2}, \quad (21)$$

where x_i, y_i were the coordinates of an agent *i*.

Statistical comparisons of means (defined over 12,000 snapshots) and variability (defined as standard deviations over 12,000 snapshots), based on $n = 100$ simulations, were performed using independent-sample t-tests. As samples were considered independent in the present study, significant ($p < 0.05$) effects were only considered when the effect size (Cohen's d) reached the minimum 0.20 threshold for a small size effect [10].

3 Results

As the individual adjustments changed (i.e., local and global modalities) for an agent in an offensive situation, the collective behaviour of the system exhibited different characteristics. These characteristics were illustrated through three different metrics: (a) metrics that measured the team center; (b) metrics that evaluated the dispersion of agents; and (c) metrics that assessed the expansion of the team.

For team center descriptions, two differents metrics were used: the mean position of the centroid (y) to determine the attack degree of a team (Fig. 2) and the variance of centroid position (x) to evaluate the capacity of the team to attack through the side or middle of the field (Fig. 3). The results showed that the centroid was situated lower on the field for a team set with a local adjustment (-19.47 ± 4.27 m) than for a team without a specific adjustment (-9.81 ± 3.94 m) (*d* = 0.11). The results also revealed that a team set with a global individual adjustment (-9.18 ± 4.39 m) played in a higher postion than a team without a specific adjustment (*d* = 1.65).

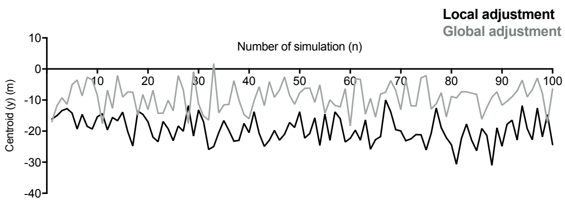

Fig. 2: Sample of the centroid (y) according to the local (black) and the global (grey) adjustment modalities

For the variance of the centroid position, the results showed that a team set with a local adjustment (9.47 ± 0.86 m) had a variation superior than a team without any adjustments (5.02 ± 0.38 m) (*d* = 4.72) or a team set with a global individual adjustment (-5.47 ± 0.44 m) (*d* = 4.12). As well, the variation of the centroid position was superior for a team set with a global adjustment when compared to a team without any specific adjustments (*d* = 0.77).

For the team dispersions, the stretch index metric was selected as the main variable. Applying the same analysis on the stretch index, the results showed that a team set with

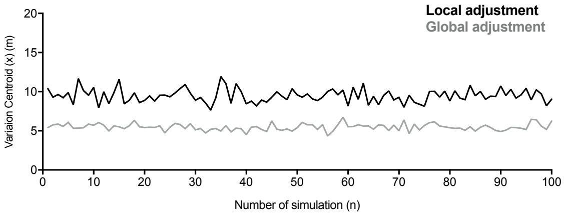

Fig. 3: Sample of the variation of the centroid position (x) according to the local (black) and the global (grey) adjustment modalities

a local adjustment modality had a higher stretch index value (21.26 ± 0.31 m) than a team without any adjustments (26.62 ± 0.27 m) (*d* d = 12.85) and a team set with a global adjustment (27.24 ± 0.42 m) (*d* = 11.39). In addition, the results revealed that a team using a global individual adjustment had a higher stretch index value than a team without any specific adjustments (*d* = 1.24).

For the team expansions, four metrics were calculated to describe the space covered by a team. Width (spread (x)) and length (spread (y)) were considered to determine the mean distance between team members, while their ratio was calculated to give an overview of the shape of the team and the convex envelope was computed to analyse the size of the surface area (Fig. 4). The results showed that a team configured with a local adjustment demonstrated a spread value (x) = 49.64 ± 1.38 m and a spread value (y) = 53.24 ± 2.19 m, which gave a ratio of 1.13 ± 0.07. The team without any individual adjustments showed a spread value(x) = 67.67 ± 0.61 m and a spread value (y) = 51.74 ± 0.91 m, which provided a ratio of 0.81 ± 0.02. The team set with a global adjustment showed a spread value (x) = 68.12 ± 0.69 m and a spread value (y) = 58.38 ± 1.81 m, which gave a ratio of (0.99 ± 0.03). Thus, the results showed that the spread value (y) of the team set with a local adjustment was lower than the team set with a global adjustment (*d* = 11.92), as was the spread value (x) (*d* = 1.80). For both spread values (x, y), the team configured without any adjustment fell between the local and global configurations.

The ratio of the team with a local adjustment was significantly higher when compared to the team without an individual adjustment (*d* = 4.31) and the team set with a global individual adjustment (*d* = 3.03). Considering the investigation of the convex envelope, the results showed that the convex envelope value of the team configured with a local individual adjustment was smaller (1,571.74 ± 47.31 m^2) than for the team without an adjustment (2,337 ± 54.77 m^2) (*d* = 10.52) and smaller than the team set with a global adjustment (2,649.66 ± 90.91 m^2) (*d* = 10.46). The convex envelope value was bigger for the team set with a global adjustment than for the team set without any specific adjustments (*d* = 2.93).

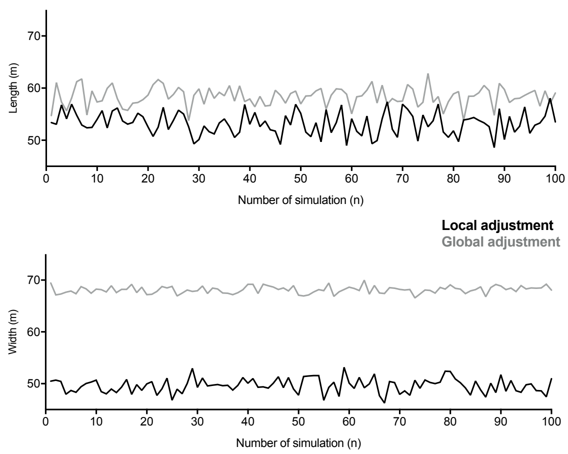

Fig. 4: Sample of the team widths and lengths according to the local (black) and the global (grey) adjustment modalities

4 Discussion

The purpose of the present study was to generate and test hypotheses about the various modalities of individual adjustment and their correlates in terms of collective behaviour emergence. The adjustment modality of a given player considered the way key spatiotemporal features of the game were grasped by player at any given moment to maintain or change current trajectories. To characterize how these adjustment modalities correlated with consequences observable at the level of collective behaviour, we constructed a model able to simulate a football game in terms of the spatiotemporal properties of organized collective behaviour. Our work assumptions were that indicators of team behaviour (like the dispersion, the centroid, and the surface area of the concerned team) were valuable metrics to capture team-level changes associated with individual adjustment variations. In line with Feigean et al. [19], which suggested that the density of spaces on the football field should be considered a key point underlying game organisation, the present study expected team metrics to vary significantly across simulation conditions, suggesting that collective behaviour changed in terms of its underlying structure. As discussed below, our results confirmed that changing adjustment modalities at the player level was associated with collective behaviour changes, while maintaining the realistic football game description. The large differences observed in the values of the metrics, according to the simulated local or global adjustment modalities, are further discussed in terms of theoretical and applied gain.

4.1 Condensed versus deployed collective behaviour

When the model was run, the related collective behaviour observed had specific properties in terms of a combination of several metric values. Our results suggested that two typical team behaviours were achieved: *condensed* and *deployed* behaviour. Condensed behaviour was mainly characterized by a small surface area. In our study, it was especially shaped as a vertical rectangle (Fig. 5) with a width smaller (spread x) than its length (i.e., spread y). When agents were positioned in such a configuration at a given instant, the stretch index was lower, indicating that players tended to be nearer to the centroid of the team than in any another configuration. Interestingly, the configuration of condensed collective behaviour was shown significantly to be the mark of a local adjustment modality. This highlights how agents being locally coupled led to an increase of team density in a given part of the field. In football terms, such an observation accounts for each player maintaining or adapting a trajectory to stay close to nearby team members, thus sharing a common playing zone. To help pragmatic interpretation, previous research conducted on football settings highlighted how creating local imbalance on specific zones of the field was of main importance [30]. Such an imbalance could be created by increasing agent closeness, as observed in the present study. Obtained through a player by player effect, local couplings gave higher density scores in only a part of the field. Thus, a local modality of adjustment afforded several opportunities to players near the ball carrier by increasing the number of players available in a small area.

By contrast, deployed behaviour was found in a larger surface area. The present study observed this surface area was shaped as a horizontal rectangle (Fig. 5) with a width higher than its length. In such a case, the stretch index was also high, accounting for players being far from the centroid of the team. This configuration of deployed collective behaviour was shown to be the significant mark of a global adjustment modality, demonstrating how agents being globally coupled led to an increase of free space over the field. In football terms, such an observation can be interpreted by the fact that players were sensitive to the distribution of player positions on the overall field, causing them to attempt movement to areas of lower density and avoid overcrowding. The desire to maintain a low density has been demonstrated as a key point for football players [19] and in line with occupying the width of a field. Taken together, the results demonstrated relationships between condensed and deployed collective behaviour and the local and global individual adjustment modalities, respectively (Fig. 5).

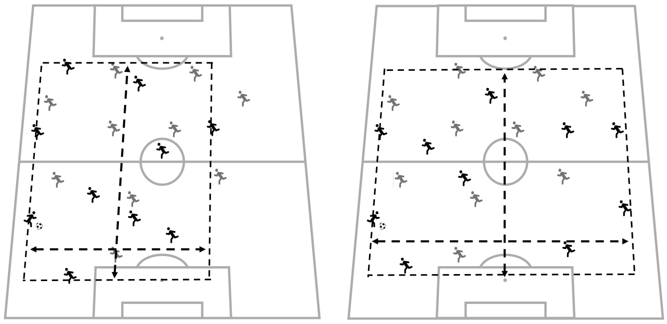

Fig. 5: Illustration of condensed behaviour (left) associated with a local adjustment modality and deployed behaviour related to a global adjustment modality (right), players in black for offense and players in grey for defense.

4.2 Advanced properties associated with adjustment modality

The individual adjustment modalities were associated with specific values and variances of the different metrics analysed. The comparison between observed team behaviour when no individual adjustment was set (i.e., adjustments only based on the football rules implemented) and any of the retained adjustment modalities (i.e., team behaviour obtained through the local or global adjustment modalities) demonstrated a significant difference in terms of the centroid positions, stretch index values, and surface area values. These results suggest that collective behaviour properties changed as soon as players began to adopt inter-individual adjustments to the ongoing situation, whether local or global. Concretely, simulations in which agents were not set with any adjustment modality could reflect real-game portions of collective behaviour in which team patterns are obtained by players not taking their behaviours into account when adapting themselves. When players regulate their behaviour based on previously built knowledge, as exemplified in the study of Feigean and colleagues [19], they can estimate how and where teammates must move, disregarding any on going consideration for the spatiotemporal situation. In the related conditions of our simulation, players obeyed shared football rules and illustrated how the concept of shared taskwork knowledge could exhibit satisfactory interpersonal behaviour while reflecting a rudimentary arrangement [4, 17].

The centroid position was shown to be lower in the local-coupling condition than in the global one. This suggests that the global adjustment modality allowed agents to move forward more rapidly and to maintain a high position on the field during the offensive phase. Indeed, when agents adjusted globally, team members distributed along the width of the field facilitated passing the ball to a forward free agents and led the team to move forward well. Conversely, the high density of players obtained in the local adjustment mode resulted in bringing more defenders towards the goal, hindering opportunities to pass the ball straight ahead and allow the offensive team to move forward. Thus, facilitated backward passes in the local coupling mode resulted in a lower centroid position of the team. In terms of metrics variance, the results showed that the variation of the centroid position (x) was higher for a local adjustment modality than for a global one. This result suggests that locally coupled team members would contribute to greater fluctuations in collective behaviour. Such fluctuations could signal a lack of patterned collective behaviour, minimizing team effectiveness. However, and in line with previous discussion of how local coupling modes can afford local game imbalance, the present fluctuations observed in the collective behaviour could indicate players looking for more opportunities to move forward on the field. The research conducted on variability in complex systems called the fluctuations shown to be beneficial to system adaptation "healthy variability" [31], and gave the label "exploration" to the process by which a system discards stable behaviour to find new solutions and create opportunities for action to achieve goals. In this sense, future research should investigate whether higher variability observed in the local coupling mode could be considered healthy and signing a functional exploration process as achieved at the scale of the team.

Understanding the functional exploration of the system would be a considerable topic for research, allowing one to build a complex social system with modalities of inter-agent adjustment that can be freely implemented. In our study, a remaining open question is whether a local or global adjustment modality would provide better team response. To our mind, the relevance and general balance allowed through a global-mode of collective adaptation should allow for better team exploration in complex settings, allowing many unexpected events to occur in an area of wide space or in any member of a large team. An increased diffusion of information could be expected by using the bird-eye-view developed by team members in such a mode, ensuring information redundancy within the system. However, a local modality of inter-agents coupling within the team should be preferred when a high sensitivity to events occurring in the nearby space of any agent is needed and when individual response to such events is considered sufficient. In such cases, a local-coupling mode could provide a high capacity to react locally, while collective behaviour would remodel after local effects spread across the team.

4.3 Limits

While our study has its strengths, it also has limitations. First, in terms of conception, this model remains rudimentary as a description of a football game, and its credibility is only based on the spatiotemporal properties of a football game. However, the model was sufficient to offer assumptions related to what kind of effects are observable as team behaviour due to changes in the nature of individual adjustment. Second, in light of our scientific contribution, it should be noted that all agents were set to the same adjustment modalities during the simulation (i.e., a perfect similarity of an individual mode within the team) while many possibilities of simulation could still be studied, including coupling-modes heterogeneity across the team members. One could also consider that actual players can change their adjustment modality across time, which should be tested in future simulations.

5 Conclusion

To conclude, the aim of our study was to explore how change in the individual adjustment modality of interacting players can be associated with significant changes in terms of collective behaviour, as observed in spatiotemporal team metrics. Among the key results, our study showed two different types of collective behaviour, condensed and deployed behaviours, associated with local and global adjustment modalities, respectively. We also described the main difference between both modes in terms of position and variability of the centroid of the team. Most of the results called for an applied consideration in terms of the density of the players, the reactiveness required for the team, and the individual and collective responses to occurring events. Future research should discuss adjustment modalities further, in terms of their functional exploration or variability, and delineate how intra-team heterogeneity and dynamics can complement the present results, when agents differ in terms of their adjustment modalities and when each of them can switch between such modalities across time.

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COMPLEMENTARY STUDY - AN EXPERIMENTAL DESIGN TO CONTROL HUMAN REGULATION

The data collection for this study was done during my master's program. Treatment of the data and the writing process were completed during Ph.D. work. This paper is in preparation and the main results are presenting in the discussion chapter.

Introduction. This study aimed to analyse processes of the emergence of collective behaviour patterns. Collective behaviour considered as self-organised emerges from individual activities that interplay as the activity unfolds. The purpose of the present study was to explore how agents actively regulate their involvement to contribute to the emergence of collective behaviour. Collective behaviour research in sport science has not considered, as often assumed in complex-systems theories, that agents couple locally per se, but that the way in which they couple has to be described empirically (Bourbousson & Fortes-Bourbousson, 2016), especially by exploring how they can act in response to their immediate understanding of the overall collective behaviour. To this end, one study has shown various informational resources that supported the regulation of individual players in football (Feigean et al., 2018). However, no studies have shown whether specific interaction rules could govern human regulation. In response to this situation, we created an experimental design in which agents have to respect specific interaction rules. We aimed at describing the variety of modes of regulation achieved by team members during two experimental situations. To conduct such a project, we adopted an epistemological approach respectful of how humans actively regulate their agent–environment coupling (AEC), which was the radically enactive perspective (De Jaegher & Di Paolo, 2007). From this perspective, sense-making was assumed to be central in delineating the dynamics of the AEC, and the phenomenological experience of the agent was seriously considered in the study design.

Method. The study involved 11 participants (Buchin et al., 2014) who volunteered to participate in the experiment. The subjects (age 21.1 $\pm$ 2.1 years) were grouped in a gymnasium of 2,175 m^2. In this study, two situations of five minutes each were performed. The subjects had to run inside the limited area while respecting an individual rule (e.g., maintain the same speed) and an interaction rule (e.g., keep a distance of 3 meters from others) designed to guide their behaviour. In addition, verbal communication was not allowed during the experiment. Before starting, researchers gave instructions that the subjects would be assessed based on their respect of the rules given. However, even though their behaviours were captured to verify compliance with the guidelines, researchers did not allocate a performance score to each. In situation 1, participants were constrained by two rules. First, we asked participants to maintain the most stable running speed possible (i.e., avoid accelerations and decelerations); they could freely choose their speed and try to keep it steady. If the speed was no longer suitable, the reference speed could be changed, but the new reference speed should be stable. Second, we asked participants to avoid entering the space near to another person. We considered this near space as an imaginary disk with a radius of 3 meters, with a participant as its centre. In situation 2, participants were constrained by two rules also. First, we asked them to maintain the most stable running speed possible, as was asked in the first situation. Second, however, participants had to move so that, from a bird's-eye view, the plot dispersion of agents formed by the runners formed a circle. We told participants that the quality of the circle would be evaluated according to its circularity, as measured by the convex envelop. Following the two experimental situations, subjects were invited to participate in self-confrontation interviews. Thematic analysis was conducted.

Results. The first objective was to characterise how participants regulated themselves to succeed in a task, which we did with a thematic analysis of their experiential data. The analysis revealed a diversity of modes of regulation in both situations (Braun & Clarke, 2006). We identified seven categories of regulation types, which we combined under two overarching themes: namely, (1) local regulation and (1) global regulation. The second objective of the analysis was to describe the extent to which the experimental conditions imposed on participants controlled their regulation modalities. The results showed that, in situation 1, participants were regulated 94.2% on the basis of local regulation and 5.8% on global regulation. In situation 2, however, individuals were regulated 13.8% from local regulation mode and 86.2% from global regulation.

Discussion. The objective was to construct experimental situations capable of governing collective behaviour based on rules imposed on the participants. Different rules were applied in the two situations as a way to differentiate the degree of individual regulation. Results suggest that various interaction rules allow for control of the regulation of the human. Moreover, the design reflects the robustness of the collective activity and the flexibility of the individual activity.

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Diversity of interaction rules in the control of human regulation An experimental design: An experimental design

Mathieu Feigean[1]

Bremgartenstrasse 145, Bern

Roland Seiler[a], Jerome Bourbousson[b]

[a]*Institute of Sport Science, University of Bern, Bern, Switzerland*
[b]*Laboratory "Movement, Interactions, Performance", Faculty of Sport Science, University of Nantes, France*

Abstract

This study aimed to analyse processes of the emergence of collective behaviour patterns. The purpose of the present study was to explore how co-agents actively regulate their involvement to contribute to the emergence of collective behaviour. Collective behaviour in sport science did not consider, as often assumed in complex-systems theories, that co-agents couple locally per se, but that the way in which they couple has to be described empirically, especially by exploring how they can act by grasping the overall collective behaviour they contribute to. To this end a study has shown various informational resources that supported the regulation of individual players in football (Feigean et al., 2018). However, no studies have investigated if specific interaction rules could govern the human regulation. In this way, we create an experimental design in which agents have to respect specific interaction rules. We aimed at describing the variety of mode of regulation achieved by team members during two experimental situations. To conduct such an ambition, we adopt an epistemological approach respectful for how human actively regulate their actor/environment coupling (AEC), that was the radically enactive perspective. The study involved

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*Mathieu Feigean

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11 participants volunteered to participate in the experiment. In this study, two situations of five minutes were performed. The subjects had to run inside the limited area, while respecting an individual rule (e.g., maintain the same speed) and an interaction rule (e.g., keep a distance of three meters with others) which aimed to guide their behaviour. In addition, verbal communication was not allowed during the entire duration of the experiment. In the situation 1, participants were constrained by two rules. First, we asked participant to maintain the most stable running speed as possible (i.e., avoid accelerations and decelerations), they could freely choose their speed and try to keep it steady. If the speed was no longer suitable, the reference speed could be changed, and the new reference speed should be stable. Second, participant had to avoid entering the space near to a person. We considered this near space as an imaginary disk with a radius of three meters, with each participant as its center. In the situation 2, participants were constrained by two rules also. First, we asked participant to maintain the most stable running speed possible as in first situation. Second, participant had to move so that, in view of an airplane, the plot dispersion of agent formed by the runners draws a circle. As a result of the two experimental situations, subjects were invited to participate in self-confrontation interviews. Thematic analysis was conducted. The thematic analysis revealed a diversity of mode of regulation in both of situations where individuals were invited to coordinate. A thematic analysis of the contents revealed 7 first-order themes of mode of regulation which where combine in two overarching themes, namely local regulation and global regulation. The results also showed that in situation 1 participants are regulated at 94.2 % on the basis of local regulation and 5.8 % of the adopted global regulation. The results show that in situation 2 individuals regulate to 3.8 % from local regulation mode and to 86.2 % from global regulation. Our objective was to construct experimental situation capable to govern the collective behaviour based on by rules imposed to the participants. Results suggest that various interaction rules allow to control the regulation of the human. Moreover the design that reflects the robustness of the collective activity and the flexibility of the individual activity.

CHAPTER 7 - GENERAL DISCUSSION

In this chapter, after a brief recap of the main objectives and results of studies, the contribution of this scientific project is described in three parts: (1) the contribution to the scientific knowledge, (2) the contribution to the epistemological and methodological knowledge and (3) the implications of fundamental findings for sport research, particularly in football.

Study 1. The first study was an exploratory study. Current research has identified the nature of the regulation performed by team members in real time as a major gap in current teamwork research (Bourbousson & Fortes-Bourbousson, 2016). When attempts were made to empirically describe the nature of the regulation supporting individual activity, those regulations were experimentally manipulated (Marmelat & Delignières, 2012). Moreover, in the past, many studies have investigated team coordination in dyads in situ (Passos et al., 2011) without considering large groups. Given this situation, the aim of the first study was to investigate the diversity of informational resources supporting individual activity when players regulate to each other. The results showed a large number of informational resources supporting the participants' activity. The results also described the complexity of regulating individual activity. Informational resources were ranked from purely local to global perceptions, including simultaneous co-occurrence of these modes and divergence from a knowledge-based regulation modality. Together, these results should be discussed in terms of focalised perceptions versus broad awareness, nearby space versus distant perceptions, and local versus global informational resources.

Study 2. The second study was a simulation study. Researchers have identified the lack of understanding of the correlation between individual activity and the patterns of spatiotemporal collective behaviour as a major gap in the current research (Feigean, Grégoire, Clément, Seiler, & Bourbousson, 2019). There is a need to generate and test hypotheses about the various modalities of individual adjustment and their correlates in emerging collective behaviour. To this end, the aim of the second study was to explore how changes in individual adjustment modalities can be associated with significant changes in collective behaviour, as observed through team-metrics values. The results confirmed that, within a model that maintained the realistic football game description, changing adjustment modalities at the player level was associated with collective behaviour changes. When the model was run, the related collective behaviour observed had specific properties in terms of a combination of several metric values. The results suggested that two typical team behaviours were achieved: *condensed* and *deployed* behaviour.

Complementary study. A complementary study was an experimental study. Much recent experimental research has focused on the interaction process, however, the investigation of large collective behaviours with experimental designs has been lacking in teamwork research. No study has shown that regulation could be governed by interaction rules. Moreover, even though Feigean et al. (2019) have studied individual adjustment in a simulation study, no study has yet investigated the link between informational resources and individual adjustments in regulation. To this end, the aim of the complementary study was to create an experimental design with specific interaction rules in each situation to investigate the modes of regulation associated with different situations. The results showed a diversity of modes of regulation in two specific situations when individuals were invited to coordinate. A thematic analysis of the contents revealed seven categories of regulation type, which were combined under two overarching themes: namely, (1) local regulation and (2) global regulation. The results also showed that, in situation 1, 94.2% of participant regulation was based on local regulation and 5.8% was based on global regulation, whereas in situation 2, individuals regulated 3.8% from local regulation mode and 86.2% from global regulation mode. Together, these results suggested that interaction rules could control the way humans regulate their behaviour to each other. It also suggested that local regulation allows greater flexibility of individual behaviour, whereas global regulation leads to greater robustness of collective behaviour.

Applied gain. The results of this research project offer applied gains. These gains are discussed in the section on the implications of fundamental findings for team sport. The benefits for coach and player are discussed.

CONTRIBUTION TO SCIENTIFIC KNOWLEDGE

The scientific contributions of this project are demonstrated in this section along several lines: a description of the investigation of the informational resources supporting regulation, a description of adjustment modalities and their correlates in collective behaviour, and a description of the ability to control human regulation. Each section below describes the major results of a study before presenting the study's limitations and suggestions about how researchers should go further to increase our knowledge about the emergence of collective behaviour. The following sections are largely inspired by the published or submitted articles included in this dissertation.

Investigation of informational resources supporting individual activity

In the literature, only a few studies have examined the way in which individuals regulate their activity within collectives. Results have suggested that agents mainly focus on local information (Passos et al., 2011). A recent opinion article suggested the possibility for global regulation (Bourbousson & Fortes-Bourbousson, 2016). A study also showed the possibility for complex regulation (Gesbert et al., 2017). However, the active regulation of individuals is mostly presupposed rather than empirically investigated. This project aimed at bridge this gap with a focus on informational resources. As a starting point, it was presumed that understanding team effectiveness in naturalistic sport settings should benefit from an investigation of how teamwork is dynamically achieved in real time. The study particularly focused on the content of informational resources that supported football players' real-time spatiotemporal adjustments on the field. The objective was to focus on the way space-time team coordination needs were enacted by the participants. In this light, the present study aimed to provide an open account of the spatiotemporal content of the informational resources that supported team members' activities as they contributed to the collective behaviour. The results revealed the spectrum of informational resources supporting team members' meaningful spatiotemporal adjustments, highlighting the relative diversity of the three main informational resources: one accounting for local information, a second for global views of the game, and a third related to previously built knowledge (Fig. 11).

Informational resources relying on a local level of organisation. In terms of local informational resources, the prevalence of relying on a single agent and relying on the ball area where current play is unfolding accounted for a perception that was very focused (i.e., agent and ball). Moreover the informational resource extracted from a broad and unfocused awareness of surrounding behaviours corresponded to a non-directed broad perception of the nearby space. Together, these aspects (and the related informational resources) were considered local because they did not require players to grasp any configuration of play or multiplayer structure. In responses to local informational resources, team members team members behaved based on being attuned to other players' attitudes, to the trajectory of the ball and/or player(s), or to any interpersonal distance.

Purely local informational resource. The first theme observed in the study aligned with existing sport science research. Indeed, informational resources relying on a single player described a given player focused on a specific behavioural variable. The given informational resource was based on the player's attitude, movement, trajectory, or interpersonal distance to another team member. Such an empirical observation thus corroborates existing studies that suggest inter-personal distance variability (Passos et al., 2011), players' velocity (Passos et al., 2008), or attacker–defender angles (Araújo et al., 2006) as good perceptions to support part of the affordances in team sport. This implies that some of the players' spatiotemporal *sense-making*, as observed on the field, was achieved by disregarding the capturing of shapes, lines, or configurations of play. This fits well with local coupling to other players and mainly nearby players. This local coupling process is in line with previous work in the ethology literature describing swarming behaviours, which has inspired sports science (Silva et al., 2014). While difficult to strictly apply to team sport, paradigmatic examples have come from the knowledge base relating to the collective behaviour of schools of fish (Couzin et al., 2002; Gautrais, Jost, & Theraulaz, 2008), whereby each fish only needs to follow simple interaction rules such as collision avoidance and maintaining inter-agent velocity. The results again illustrate how a local coupling process may develop on the field of naturalistic football, disregarding how teamwork emerges at the team level. Interestingly, this informational resource was predominant (Feigean et al., 2018), thus confirming the relative relevance of affordance-based descriptions of collective behaviour in sport, mainly grounded on this assumption.

Extended informational resource. The informational resource identified as relying on a comprehensive awareness of proximal surrounding behaviours implied that a given player aimed at being sensitive to all neighbouring events the player was able to grasp. In such cases, players exhibited a radar-like awareness with a sweeping perception of the nearby environment, waiting for any local event to become meaningful and support how they regulated their behaviour. Such awareness was referred to as a local way of regulating individual contributions to collective behaviour.

Environmental local informational resource. The theme describing informational resources that relied on the ball area where the current play is unfolding considered that players regulate their own behaviour via a geographically transferred awareness (i.e., towards the ball area), sometimes located far from the given player's nearby space. In this case, players' activities were viewed as again supported by local informational resources even when resources were outside the surrounding space. For a given player, this way of regulating his interacting activity invites researchers to be cautious when assimilating the notion of perceptual focalisation with that of nearby space awareness. Interestingly, when one considers that many players can simultaneously monitor the ball area while not adjusting their respective behaviours through direct regulation with other players, the resulting collective behaviour should be described as an indirect mode of coordination (Gesbert, Durny, & Hauw, 2017). As previously evidenced in basketball (Bourbousson, R'Kiouak, & Eccles, 2015), convergent/coordinated behaviours of team members can be achieved by sharing similar informational resources, without each player necessarily taking his teammates into account. R'Kiouak, Saury, Durand, and Bourbousson (2017) recently elaborated on the fundamentals of such a process in their stigmergic view of teamwork. In their study of a rowing setting, team members exhibited highly synchronised patterns of collective behaviour, achieved not by direct co-awareness of their behaviours but by engaging individual activities that were supported by a simultaneous awareness of their shared environment (i.e., the boat in the study setting). This regulation has been illustrated in the literature with the concept of *stigmergy* (Grassé, 1959).

Importance of informational resources relying on a global level of organisation. Contrary to local resources, global resources rely on a global spatiotemporal shape, thus referring to a perception of the spatiotemporal configuration of a given unit of agents (e.g., defenders, attackers or the whole team) or a perception of a given space (e.g., free space). These themes thus correspond to the regulation in which participants behave in response to regarding the overall spatiotemporal state of the players, being particularly sensitive to density (i.e., low or high) in the given space.

Purely global informational resources. When players' activities were supported by informational resources relying on a spatiotemporal shape within the game, the players perceived game events as if they were capable of a bird's-eye viewpoint. This led them to build either a global perception of their own team behaviour (e.g., positioning of defensive and offensive lines) or a perception of the density of players within certain areas on the field (i.e., looking for free space). Surprisingly, the research on collective behaviour has overlooked the capability of human team members to grasp in real time the global picture (Bourbousson & Fortes-Bourbousson, 2016). The only proposal we found in the literature was by Grehaigne et al. (2011), but such a perception of the configuration of play was mainly presupposed rather than empirically documented (Grehaigne et al., 2011). Another insight comes from a game analysis study that showed how individual behaviour in team sports can be more constrained by collective behavioural variables than by local ones. Basketball players' dribbling to the basket (i.e., driving) was shown to be supported by a disruption of the relationship between the opposing team’s centroid and stretch index rather than being supported by the events occurring in the attacker–defender dyad (Grehaigne et al., 2011). To illustrate, a recent study investigated individual dancing in a social situation. Results showed how participants could perform feats while being aware of the movement of every other participant and while moving on a very large dance floor (Long, Jacob, Davis, & Magerko, 2017). Thus, research supports a distinct sensibility phenomenon of being aware of the individual motions of every player on the team (Long et al., 2017). In other words, one should not confuse exhaustive local couplings with adapting one's behaviour vis-à-vis the global dynamics of the social system as a whole. Empirical evidence of holoptism in human movement science has recently been found in the literature (Bourbousson & Fortes-Bourbousson, 2016).

Complex informational resources. In addition, the informational resources relying on the simultaneous consideration of a single player and a spatiotemporal shape suggest that players can also mix global and local resources, as when being attuned to different simultaneous and distinct targets. The activity of players was here experienced as the hard task of sharing attention by monitoring two concomitant informational resources of diverging natures. Interestingly, local and global modes of regulation were time-chained together in the dynamics of the game. The results also show how global perceptions did not exclude local ones when considering a single instant. From an intuitive standpoint, such a combination of local and global informational resources can represent a powerful mode of perception, making both informational resources work together to build the experiential picture from which the player makes decisions. In such a case, the team member was simultaneously able to ensure the relevance of his or her activity in the vicinity by managing local couplings (e.g., monitoring the nearby space) and to update or challenge how he or she behaved locally by monitoring states of effective teamwork patterns (Gesbert et al., 2017). This mixed mode of regulation has been described as an adjustment of activity based on the distance variable. For Gesbert et al. (2017), the mixed regulation combined a regulation with a nearby individual and with a more distant individual. First, Gesbert et al. (2017) are not clear in the definition of regulation, informational resources (i.e., perception) and adjustment. Second, the study has distinguished local regulation and global regulation through the distance variable. This present project refutes this idea. Indeed, even if the local informational resource most often relates to the nearby space, it could also be relevant for a more distant individual. The proximal distance is not totally linked with a local informational resource. However, this mixed regulation tell that players combine at the same time various informational resources.

Representations as informational resources. Amongst the informational resources observed, one theme was found to be very specific and did not fall into the previous continuum between local and global informational resources. This was an informational resource relying on previously built knowledge suggesting event(s) expected to happen. We considered it inappropriate to discuss this *representational* resource in the same way as local/global informational and contextual resources. Indeed, this theme accounted for a team member's activity regulated on the basis of virtual expectations, and not on the current situated perceptions of the player. These expectations were generated by the players based on their previous football experience, which allowed them to anticipate probable event(s) without the need to check the current real situation. Finally, informational resources relying on previously built knowledge suggesting events expected to happen have been mentioned in previous research. In this light, the social-cognitive perspective of team coordination (Eccles & Tenenbaum, 2004) assumes that patterned teamwork mainly arises through sharing knowledge within the team, which refers to similar representations of the task and the team routines across team members. According to this approach, shared knowledge helps team members form clear expectations about others' actions so that situational probabilities (as conceived in the head of the player) can support the way each teammate behaves, rendering real-time event monitoring and related cognitive interpretation not always necessary (e.g., as in performing a no-look pass).

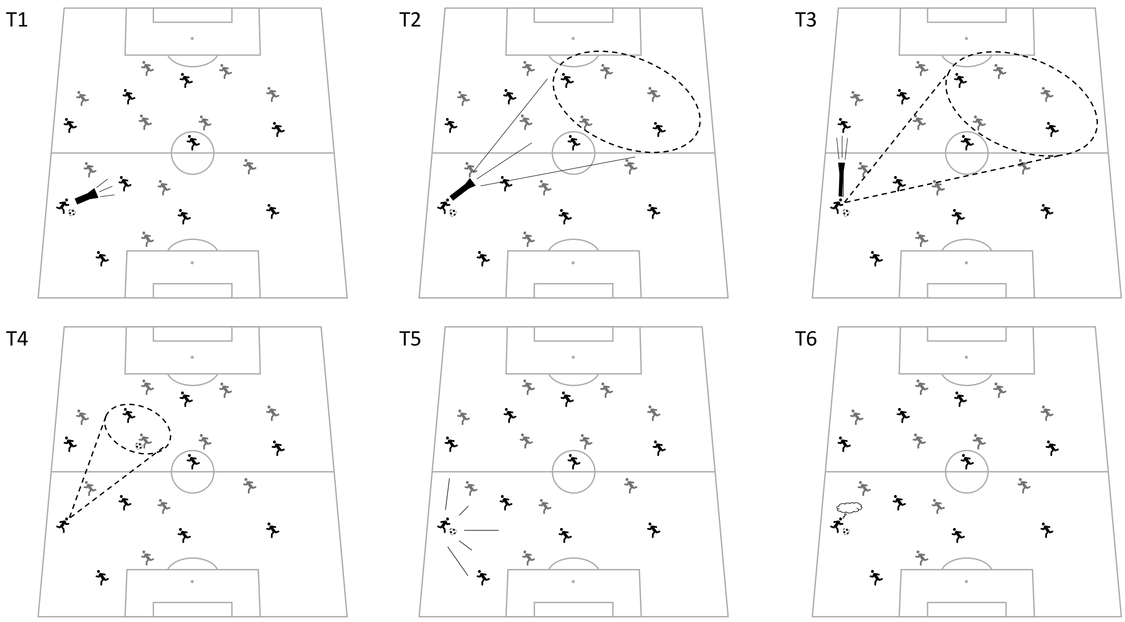

Figure 11. Informational resources supporting the players' activities at a given instant within a team: (T1) relying on a single agent, (T2) relying on a global spatiotemporal shape, (T3) relying on a simultaneous consideration for an agent and a global spatiotemporal shape, (T4) relying on the ball area where current play is unfolding, (T5) extracted from a broad and unfocused awareness of surrounding behaviours and (T6) relying on previous built knowledge suggesting an event expected to happen (Feigean et al. 2018).

Limitations. This studied investigated informational resources to advance our knowledge about individual regulation. However, the study did not show any relation between the informational resources and the collective activity arising from them. In other words, this study does not provide any argument to justify the efficiency of local or global individual resources in the elaboration of collective behaviour. Second, considering regulation as a combination of informational resources and the adjustment supporting player activity, there is no certitude that a local informational resource implies a local adjustment. For example, a global perception of the game can result in a local adjustment such as maintaining the distance to the closest players. In this case, the player uses a global informational resource to locally adjust his or her behaviour. Further study should investigate this limitation.

***For further research*.** Together with the results discussed in the previous sections, the study suggests that future research should better distinguish between the underlying states of perceptual readiness involved, such as distinguishing between being focused (i.e., focalising) and staying aware (i.e., with a radar-like involvement). The process of constructing expertise in contributing to team behaviour should probably include training practices and mental preparation that alternates between both kinds of perceptual readiness, because the two would probably not be governed by similar mental skills. The results also suggest further areas for potential investigation. First, the first study does not consider the different positions of the players (e.g., defenders, attackers). Second, given that a large group was studied, it could be interesting to study other group sizes to understand in which conditions holoptism could occur. Do players need to grasp the overall picture when the size of the team is small or more when the size of the group is big? For example, Assemat, K. (2012) showed that the riders in cycling need to have information about the overall state of the peloton to adjust their behaviour. Riders want to know which riders are at the head of the race and also how team members are placed in the peloton. Moreover, the shape of the interdependence (Saavedra, Earley, & Van Dyne, 1993) between players could also impact the necessity for a player to grasp the overall picture of the team. Third, the distribution of informational resources between players over time was not considered, and it is probable that the capability to switch between local and global modes of regulation could be an important area of expertise to be considered. The different informational resources used by players during the recorded sequence are illustrated according to the time in the sequence (Fig. 12). This observation comes from a data set collected for the first study, however a deeper investigation is necessary to obtain relevant results.

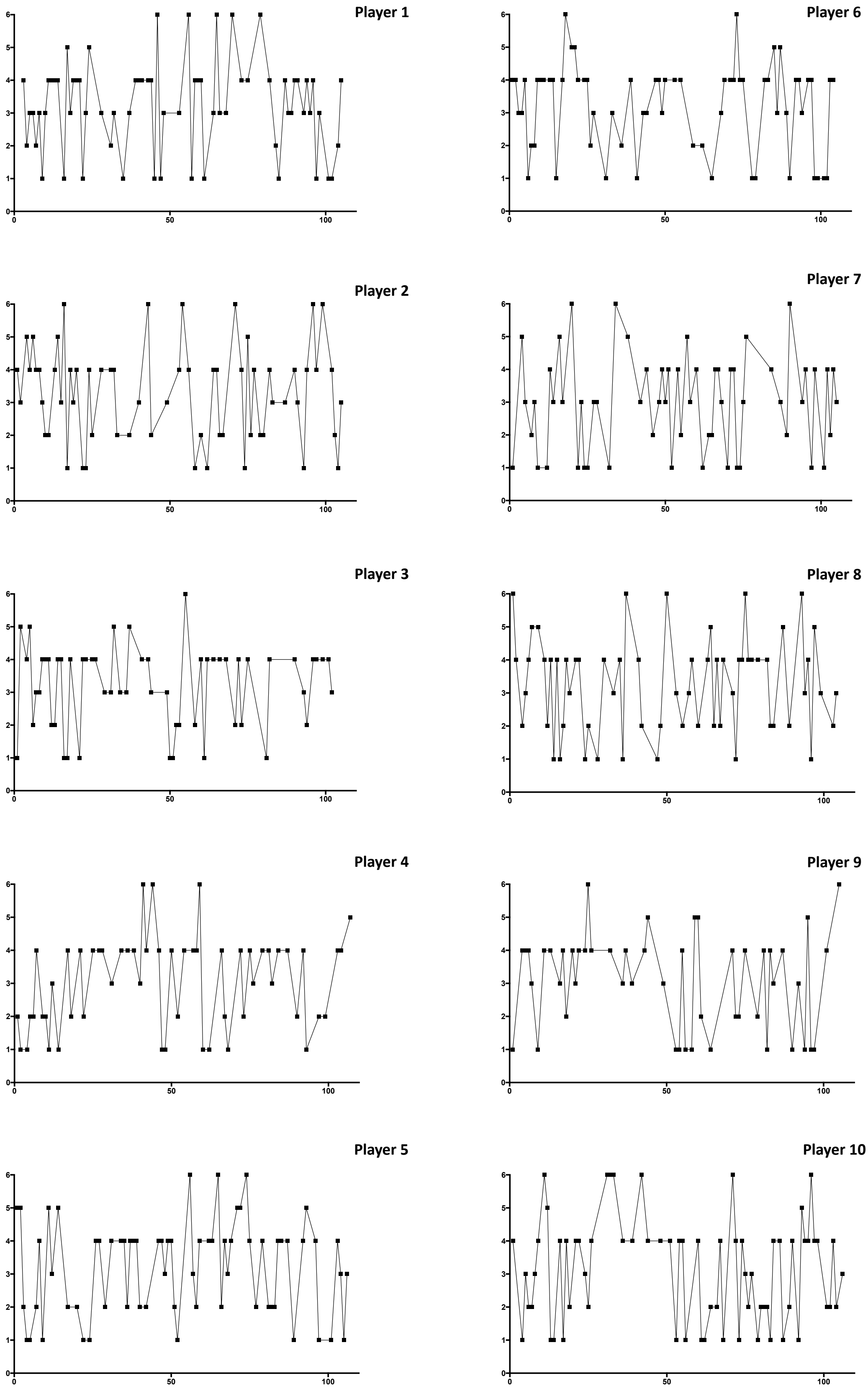

Figure 12. Illustration of the informational resources supporting the players' activities during the sequences according to the time of the sequence. From the top left to the bottom right, player 1 to player 10. 1 to 6 informational resources are respectively the same than the figure 11.

Finally, the positions of the player could be investigated based on several hypotheses. For example, it is possible to assume that the defender could use more global informational resources to get an overview of the situation and help team members to move to acceptable positions on the field. Midfielders aim at organising overall game strategy and thus could use informational resources extracted from a broad and unfocused awareness of surrounding behaviours. This resource affords the possibility of choosing the more efficient action to score a goal. Finally, attackers with an aim of scoring could use informational resources relying on the ball area where current play is unfolding. This resource may allow them to always be efficiently placed to get the ball. A profile of all players is given (Fig. 13).

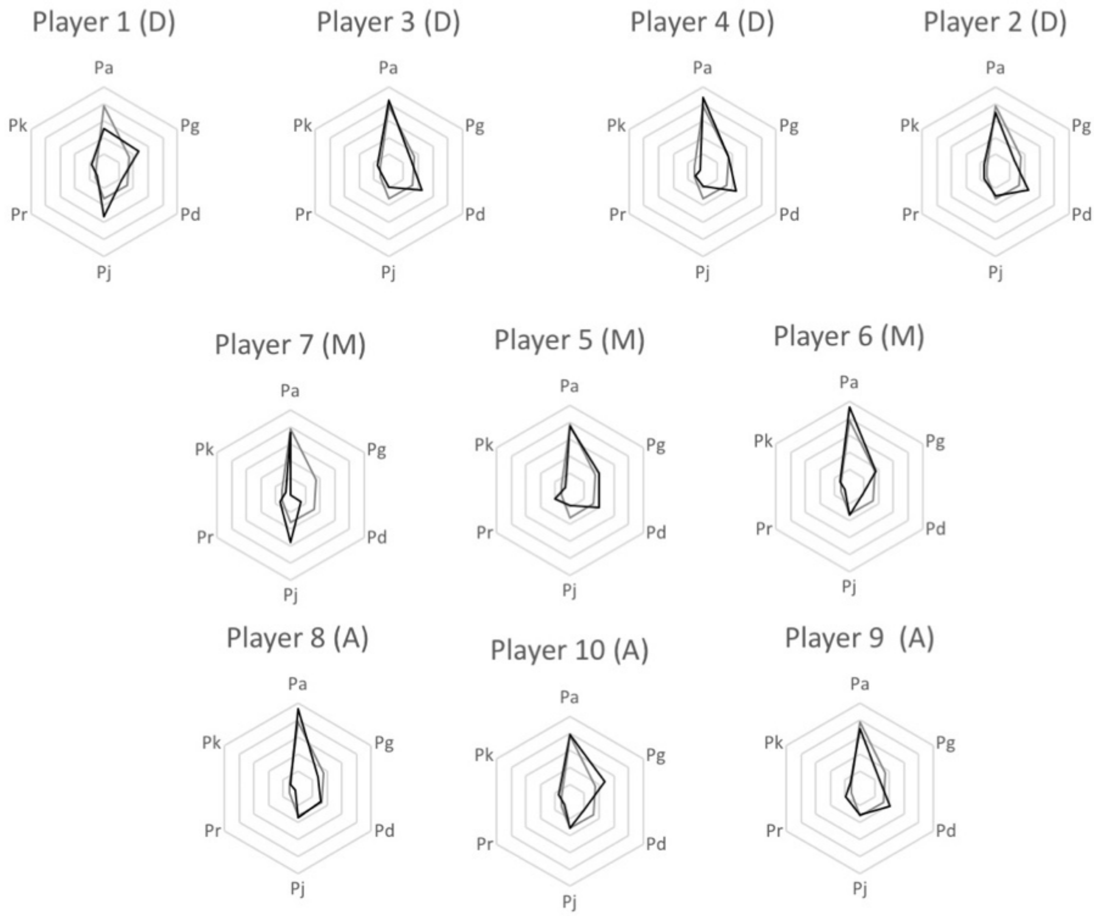

Figure 13. Illustration of profiles for all players. In grey is the mean profile of team members. Individual profiles are in black. (Pa) informational resources relying on a single agent, (Pg) informational resources relying on a global spatiotemporal shape, (Pd) informational resources relying on a simultaneous consideration for an agent and a global spatiotemporal shape, (Pj) informational resources relying on the ball area where current play is unfolding, (Pr) informational resources extracted from a broad and unfocused awareness of surrounding behaviours and (Pk) informational resources relying on previous built knowledge suggesting an event expected to happen.

Individual adjustment through correlate collective behaviour

The first study focused on the informational resources supporting regulation; the second study focused on the adjustment. In the literature, many studies have examined collective behaviour using simulations. Examples include a study in ethology (Couzin et al., 2002) and a study in physics involving pedestrian behaviour (Helbing & Molnár, 1995). However, in the field of sport science, team behaviour simulation studies are not common. In the research on collective behaviour, there is no clear study that has investigated the correlation between individual adjustment modality and collective consequences that are observable in the spatiotemporal behaviour. We have aimed to bridge this gap.

Test hypotheses. To investigate the correlated collective behaviour, this study aimed to test hypotheses about varying the adjustment and observing the consequences at the level of collective behaviour. To this end, we constructed a simulation model to test hypotheses about local versus global individual adjustment thus we analysed the spatiotemporal characteristic. In this study, the adjustment was simulated after considering what informational resources could result in such an adjustment. In other words, the construction of the adjustment was based on the results from the first study. When the model was run, the related collective behaviour observed had specific properties in terms of a combination of several metric values. The results suggested that two typical team behaviours were achieved, which were called *condensed* and *deployed* behaviour.

Condensed behaviour. Condensed behaviour was mainly characterised by a small team surface area (Fig. 14). In this study, it was specifically shaped as a vertical rectangle with a width smaller (spread *x*) than its length (i.e., spread *y*). When agents were positioned in such a configuration at a given instant, the stretch index was lower, indicating that players tended to be nearer to the centroid of the team than in any another configuration. Interestingly, the configuration of condensed collective behaviour was shown significantly to be the mark of a local adjustment modality. This highlights how agents being locally coupled led to an increase of team density in a given part of the field. In football terms, such an observation accounts for each player's maintaining or adapting a trajectory to stay close to nearby team members, thus sharing a common playing zone. It may help pragmatic interpretation to look at previousresearch conducted on football settings highlighted how creating local imbalances in specific zones of the field was of main importance. Such an imbalance could be created by increasing agent closeness, as observed in the present study. Obtained through a player by player effect, local couplings gave higher density scores in only a part of the field. Thus, a local modality of adjustment afforded several opportunities to players near the ball carrier by increasing the number of players available in a small area.

Deployed behaviour. By contrast, deployed behaviour was found in a larger surface area. The present study observed this surface area was shaped as a horizontal rectangle (Fig.

14) with a width higher than its length. In such a case, the stretch index was also high, indicating players were far from the centroid of the team. This configuration of deployed collective behaviour was shown to be the significant mark of a global adjustment modality, demonstrating how agents being globally coupled led to an increase of free space over the field. In football terms, such an observation can be interpreted as players being sensitive to the distribution of player positions on the overall field, causing them to attempt movement to areas of lower density to avoid overcrowding. The desire to maintain a low density has been demonstrated as a key point for football players and in line with occupying the width of a field. Taken together, our results demonstrated relationships between condensed and deployed collective behaviour and the local and global individual adjustment modalities, respectively.

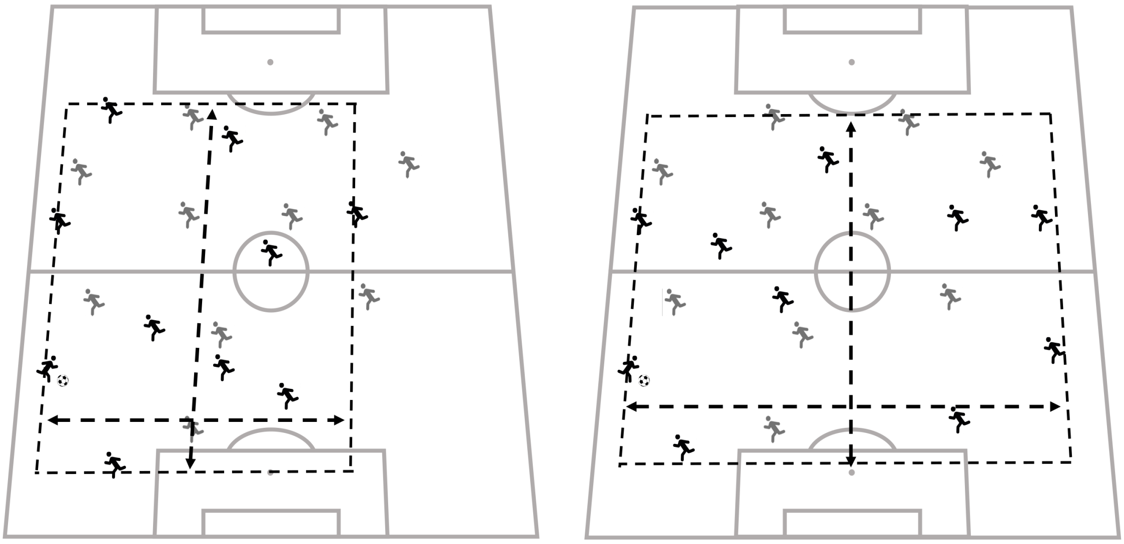

Figure 14. Example of condensed behaviour (left) versus deployed behaviour (right).

Advanced properties. The individual adjustment modalities were associated with specific values and variances of the different metrics analysed. The comparison between observed team behaviour when no individual adjustment was set (i.e., adjustments were based only on the football rules implemented) and any of the retained adjustment modalities (i.e., team behaviour obtained through the local or global adjustment modalities) demonstrated a significant difference in terms of the centroid positions, stretch index values, and surface area values. These results suggest that collective behaviour properties changed as soon as players began to adopt inter-individual adjustments to the ongoing situation, whether local or global. Concretely, simulations in which agents were not set with any adjustment modality could reflect real-game portions of collective behaviour in which team patterns are obtained by players not taking their adjustment to each other. When players regulate their behaviour based on previously built knowledge, they can estimate how and where teammates must move, disregarding any on-going consideration for the spatiotemporal situation. In the related conditions of our simulation, players obeyed shared football rules and illustrated how the concept of shared taskwork knowledge could manifest itself as satisfactory interpersonal behaviour while reflecting a rudimentary arrangement

(Blickensderfer et al., 2010; Eccles & Tenenbaum, 2004). The centroid position was shown to be lower in the local-coupling condition than in the global one. This suggests that the global adjustment modality allowed agents to move forward more rapidly and to maintain a high position on the field during the offensive phase. Indeed, when agents adjusted globally, team members distributed along the width of the field facilitated passing the ball to forward free agents and led the team to move forward well. Conversely, the high density of players obtained in the local adjustment mode resulted in bringing more defenders towards the goal, hindering opportunities to pass the ball straight ahead and allowing the offensive team to move forward. Thus, facilitated backward passes in the local coupling mode resulted in a lower centroid position of the team. In terms of metrics variance, the results showed that the variation of the centroid position (x) was higher for a local adjustment modality than for a global one. This result suggests that locally coupled team members would contribute to greater fluctuations in collective behaviour. Such fluctuations could signal a lack of patterned collective behaviour, minimizing team effectiveness. However, and in line with previous discussion of how local coupling modes can afford local game imbalance, the present fluctuations observed in the collective behaviour could indicate players looking for more opportunities to move forward on the field. Research conducted on variability in complex systems calls those fluctuations shown to be beneficial to system adaptation *healthy variability* (Seifert, Button, & Davids, 2013) and gives the label *exploration* to the process by which a system discards stable behaviour to find new solutions and create opportunities for action to achieve goals. In this sense, future research should investigate whether higher variability observed in the local coupling mode could be considered healthy and signalling a functional exploration process achieved at the scale of the team.

Build a complex system. Understanding the functional exploration of the system would be a considerable topic for research, allowing one to build a complex social system with modalities of inter-agent adjustment that could be freely implemented. In our study, a remaining open question is whether a local or global adjustment modality would provide better team response. To our mind, the relevance and general balance found in a global-mode of collective adaptation should allow for better team exploration in complex settings, allowing many unexpected events to occur in an area of wide space or to any member of a large team. An increased diffusion of information could be expected by using the bird's-eye view developed by team members in such a mode, ensuring information redundancy within the system. However, a local modality of inter-agent coupling within the team should be preferred when a high sensitivity to events occurring in the space nearby any agent is needed and when individual response to such events is considered sufficient. In such cases, a local-coupling mode could provide a high capacity to react locally, while collective behaviour would remodel after local effects spread across the team.

Limitations. While the study has its strengths, it also has limitations. First, in terms of conception, this model remains rudimentary as a description of a football game, and its credibility is based only on the spatiotemporal properties of a football game. However, the model was sufficient to generate assumptions related to what kind of effects are observable in team behaviour due to changes in the nature of individual adjustment. Second, in light of our scientific contribution, it should be noted that all agents were set to the same adjustment modalities during the simulation (i.e., a perfect similarity of adjustment modality within the team), while many possibilities of simulation could still be studied, including coupling-mode heterogeneity across team members. One could also consider that actual players can change their adjustment modality over time, which should be tested in future simulations.

For further research. First, the previous study focused on individual adjustment. This adjustment was similar for all players on the team and throughout the simulation. From this point, two interesting studies could be relevant. First, it is assumed that all players use various adjustments in natural setting situations, so that their capability to switch between local and global adjustment modalities could be one important area of expertise to be considered. To do that, the code programmed in the last study also included a function called *adjustment generate* that can generate an adjustment modality randomly at each time step. Secondly, it is probable that defenders, midfielders and attackers do not all make the same adjustments. Research focused on this could increase the validity of the model. Moreover, the model focuses only on the global and local adjustment modality. Feigean et al. (2018) showed a large diversity of possible adjustments, and the next study should increase the number of the possible adjustments. The objective of the study started as an attempt to develop the adjustment to the ball by changing behaviour according to the distance to the ball. Finally, Feigean et al. (2019) have shown from a simulation study a potential to generate hypotheses about correlations between individual players' regulation and collective behaviour patterns. However, an experimental design that also controls regulation could increase the power of generalisation of these hypotheses.

Delineating and controlling individual regulation.

Our objective was to construct an experimental situation capable of providing interactional rules imposed on the participants that could control individual regulation modalities. Two situations were elaborated with different specific rules as a way to differentiate the individual regulation. In the first situation, agents were constrained by local interaction rules, whereas in the second situation, agents were constrained by global interaction rules. Situations had to influence regulation modalities but also allow the expression of participant autonomy. Before investigating the ability to control individual regulation, the first objective was to delineate regulation according to the concepts of informational resources and adjustments.

Informational resources and individual adjustment within regulation processes. The study's thematic analysis revealed a wide variety of regulation modes (Braun et al., 2016). These have been categorized into four main themes. On one hand, regulation could arise from a local informational resource and resulting either as local or a global adjustment. On the other hand, regulation could arise from a global informational resource and resulting either as local or global adjustment. All regulation modalities were labelled (1) local adjustment based on local informational resource, (2) global adjustment based on local information resource, (3) local adjustment based on global information resource and (4) global adjustment based on global informational resource (Table. 1). The modes of regulation are discussed as three entities: those labelled (a) were considered local regulations and those labelled (b) were considered global regulations. Others were described as mixed regulation.

Verbatim	**Informational resources**	**Adjustments**	**Modes of Regulation**
"I see this guy taking the road that I wanted to take, so I change my direction, I slow down to do not be too close from him"	Local	**Local** Avoidance	**Local adjustment based on local informational resource**
"At this time, I try to follow him, and keep the distance to him"		**Local** Follow-up	
"I continue to look in front of me, but for now everything is good, I stay like this"		**Local** Hold	
"It's the man in white there who also begins to return to in the circle, so I'm going in free space"		**Global** Free space / Shape	**Global adjustment based on local informational resource**
"Everyone runs at the speed, I hold on to the one in front of me"	**GLOBAL**	**Local** Follow-up	**Local adjustment based on global informational resource**
"I try to go where people do not go and find free spaces"		**Global** Free space	**Global adjustment based on global informational resource**
"I do about the same circle as the group"		**Global** Shape	

Table 1. Examples of verbalisations collected from self-confrontation interviews and the related informational resource and adjustments to give the regulation modalities as themes.

An experimental design that controls individual regulation. The experimental design seemed effective in manipulating the desire of an individual to regulate his or her behaviour in a certain way. The situation constructed to induce local individual regulation showed that in 94.2% of cases the local regulation was adopted. The situation constructed to induce global individual regulation show that in 86.2% of cases, participants adopted this regulation in this situation. Thus, the experimental rules imposed on participants had an impact on individual regulation. However, neither of the two situations fully induced the expected individual regulation. In other words, there were moments when some participants did not adopt the preferred regulation. In some cases, the study design is no longer sufficiently to control a specific regulation and individuals tend to change their regulation. It has been assumed that these changes in regulation are likely to reflect individual or collective behavioural disturbances that result in individuals being adapted to the situation to ensure their viability. When the group is disorganised, changing the regulation would likely allow a return to a stable state of the group. It is this assumption that will be supported by the analyses discussed below. In sum, the constructed experimental situations seem usable for putting participants in a position to contribute to collective behaviour, while at the same time controlling, to a large extent, the informational resources they adopt. This design can be a basis for apprehending collective phenomena in an experimental approach.

A design reflecting the robustness of collective activity and the flexibility of individual activity. The two experimental situations allow us to discuss an essential point, that of the control of collective activity. Here, we attempted to control human regulation supporting collective activity on the basis of interpersonal constraints imposed by experimental guidelines. This resulted in a commitment to the expected task constraints on the part of participants, leading to a certain robustness of the collective behaviours produced. The collective system maintained the properties of its activity according to constraints. However, the results showed a certain flexibility of collective activity, the capacity of the complex system to modulate its organisation with respect to contextual variations, through the regulation of individual behaviour. Individuals were able to make choices about their own behaviour that made them free without causing chaos at the level of collective organisation. Interaction rules that involved local regulation induced more flexibility in the modes of regulation (i.e., more frequent changes), associated with a greater concomitant fragility of collective behaviour (i.e., spatiotemporal data). In sum, if the robustness of a complex system is defined by its sensitivity and resistance to disorder (internal or external), the collective behaviours generated by local interaction rules (i.e., by an essentially local regulation mode) were less robust than those generated by global interaction rules. Together, these results suggest that the adoption of a given regulation modalities (i.e., local vs global) has implications for collective products, their dynamics, and their fragility. To conclude, our study first revealed the diversity of regulation, taking into account information resources and adjustments, in the elaboration of collective behaviour.

For further research. Although spatiotemporal data were collected, their treatment was not sufficiently rigorous to produce publishable results. However, the articulation of experiential and behavioural data would account for the interference between levels in the collective behaviour and, thus, supplement the hypothesis of top-down and bottom-up causalities. This study also offers benefits for simulation studies. Indeed, the movements within schools of fish are mainly understood using interaction rules. Control of the interaction rules (i.e., regulation modalities) gives rise to specific collective behaviours. Thus, to create collective behaviour at the level of the human, it is necessary to control their regulation.

Eyes on the future

A future project aims to identify the spatiotemporal conditions of efficiency for these different regulation modalities in relation to the emerging collective properties driven by them.

From simulation study to natural setting. Another future project could attempt to analyse the emerging phenomena in a natural football setting. This project will be developed in two stages. Based on naturalistic sport settings, the first stage will attempt to understand how individual regulation may contribute to variations of collective organisation and to identify the sensitiveness of the system to individual changes. In the second stage, the aim will be to investigate spatiotemporal data by looking at what happens in individual regulation when the behavioural data are stable and also when the behavioural data are unstable. To this end, subjective data about individual regulation will be collected and connected to behavioural data to observe the variation.

Subjective data analysis. Subjective data are collected during self-confrontation interviews and transcribed. A temporal synchronization of the time of the action and the time of the transcript is performed. For each individual, a temporal scale marked to the second was constructed to account for the modes of regulation adopted at each moment (Table. 2). According the complementary study, modes from 1 to 4 correspond to local regulation mode and those from 5 to 7 correspond to global regulation mode. At this end, we combine the temporal scale for all the participants.

Participant 1																		
Time (s)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	…
Regulation modalities	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	
Participant 2																		
Time (s)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	…
Regulation modalities	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	
Participant 3																		
Time (s)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	…
Regulation modalities	1	1	1	3	3	3	3	3	3	6	6	6	3	4	4	4	4	
Participant 4																		
…																		

Table 2. Examples of participant regulation over the time. The local regulation is numbered from 1 to 3, the global regulation is numbered from 6 to 7, and the mixed regulation is numbered 4 and 5.

Behavioural data treatment. From the positional data, measures are calculated to evaluate the individual activity (Fig. 15). The calculated individual data are for example, the speed at each moment, the number of people within a 5-meter radius, and the lateral (y) and longitudinal (x) trajectory of the participants.

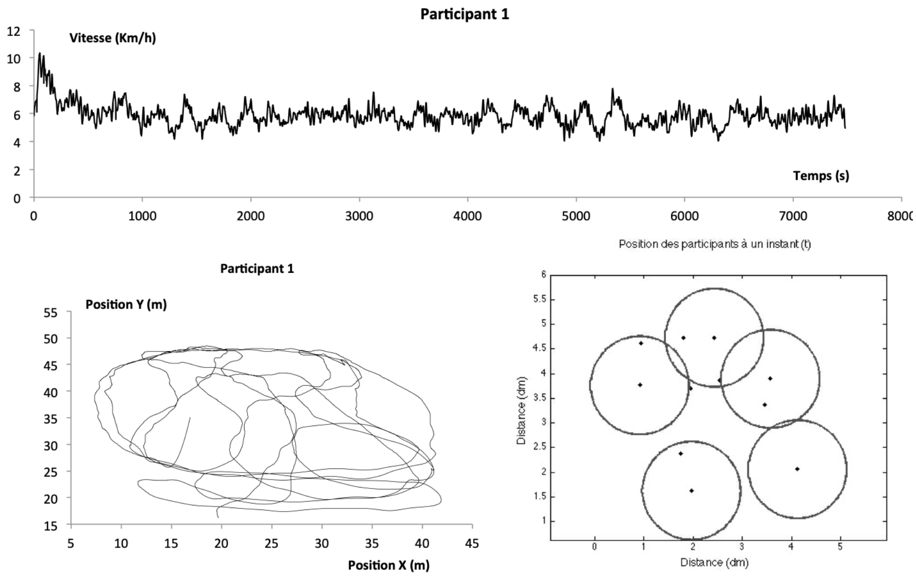

*Figure 15***.** Illustration of individual spatiotemporal data, velocity of the player, trajectory of the player and circle with 3-meter radius.

From the positional data, measures are calculated to assess the collective metrics, as the centroid, stretch index, and surface area (Fig. 16).

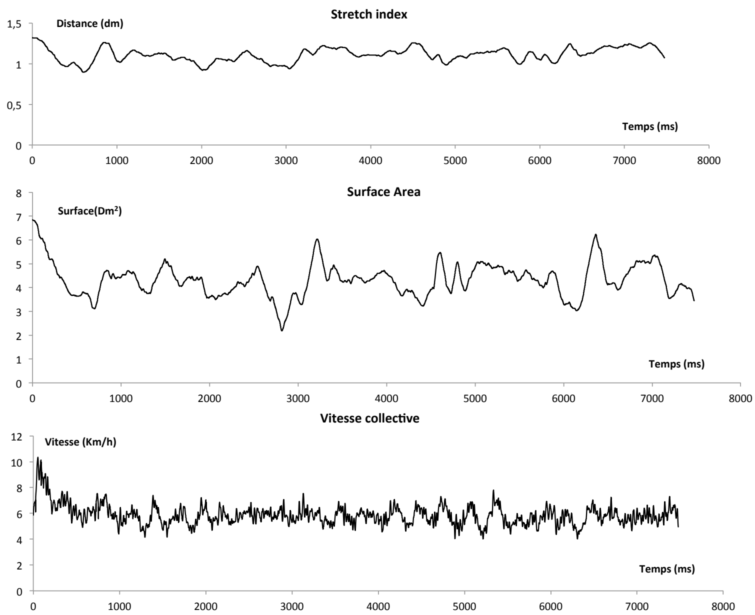

Figure 16. Illustration of collectives variables, stretch index, surface area and mean velocity of the team.

Articulation of subjective and behavioural data. In terms of the subjective data, three periods in the scale are of particular interest. The first is the period when all players share the same regulation modalities, the second is the period when players use various modes of regulation, and the last is the period in which one player switches from regulation modalities to another (Table. 3). Based on this treatment, we selected a sample of the corresponding behavioural data. We then compared the behavioural data according to the different periods.

Participant 1																		
Time (s)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	…
Regulation modalities	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	
Participant 2																		
Time (s)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	…
Regulation modalities	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	
Participant 3																		
Time (s)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	…
Regulation modalities	1	1	1	3	3	3	3	3	3	6	6	6	3	3	3	3	4	
Participant 4																		
…																		

Table 3. Illustration of the different samples. Those in blue precede an individual change of regulation mode, those in green represent periods in which at least one person diverged from regulation mode and those in red represent periods in which the entire sample is in the same regulation modalities.

One other way to analyse the data is to observe the disruptions in the spatiotemporal data and check the subjective data to determine what happened in terms of individual regulation at those points (Fig. 17)

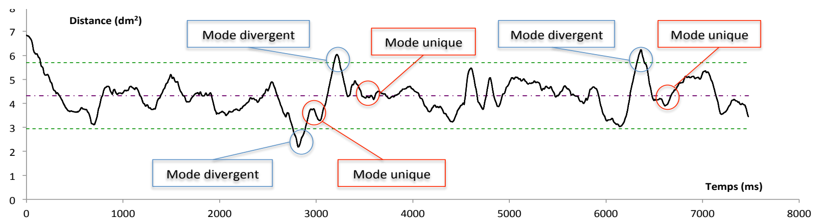

Figure 17. Illustration of the divergent vs unique modes of regulation, according to the surface area.

Expected results. Here we present some expected results. For example, Table. 4 shows a comparison of the mean and the variation of different metrics during two periods of individual regulation. In the standard period, all players shared the same individual regulation. In the change period illustrate the moment before that a player switch to another regulation modality.

Fig. 18 illustrates the mean centroid and stretch indices of a team in two situations: (1) when all players regulates their behaviour in the same way, and (2) when one or more players will switch from a local regulation to a global regulation in the next seconds (Fig. 18).

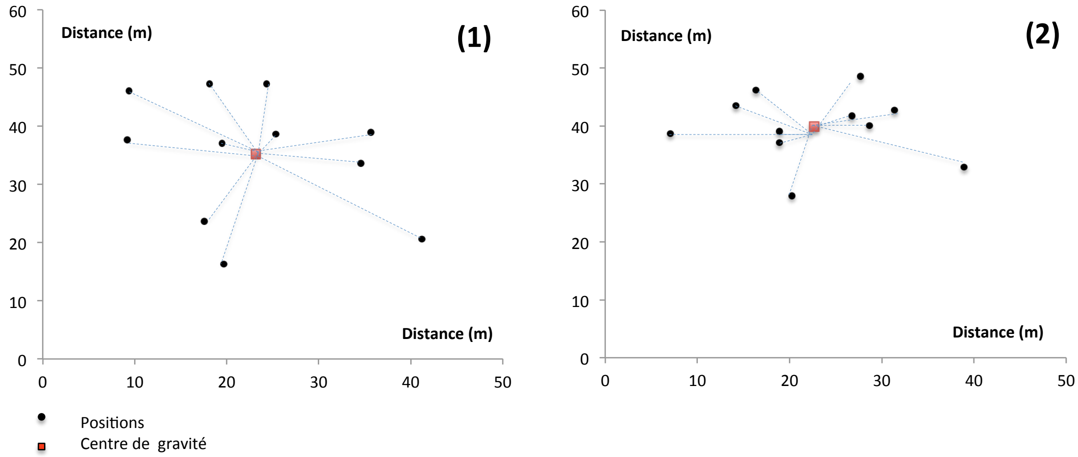

Figure 18. Stretch index during two periods. The period (1) illustrate a situation when players all the players keep the regulation modalities whereas the period (2) illustrate a situation when players tend to switch to a regulation modality to another one.

Fig. 19 illustrates the mean surface area of a team in two situations: (1) when all players regulates their behaviour in the same way, and (2) when one or more players will switch from a local regulation to a global regulation in the next seconds (Fig. 19).

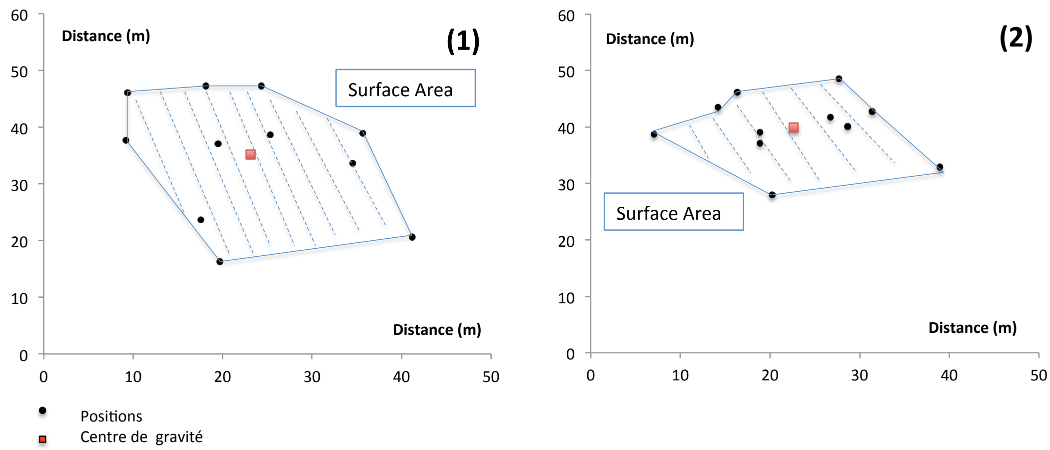

Figure 19. Surface area during two periods. The period (1) illustrate a situation when players all the players keep the regulation modalities whereas the period (2) illustrate a situation when players tend to switch to a regulation modality to another one.

CONTRIBUTION TO EPISTEMOLOGICAL AND METHODOLOGICAL KNOWLEDGE

This project has adopted several methodologies. In this section, we present the contributions to epistemological and methodological knowledge. This section presents four main contributions: (1) a discussion about theoretical concepts through the enactive approach, (2) the subjective approach as a priority, (3) the transformation of subjective data to equations and (4) the simulation study as an innovative methodology in sport science.

Theoretical concepts - Affordances stigmergy and holoptism

The first study of the project showed the various informational resources that players used. These informational resources are all associated with theoretical concepts which are discussed here within the framework of the enactive approach.

Affordance concept. The results of the first study showed that players used informational resources extracted from a broad and unfocused awareness of surrounding behaviours. Such broad attentional readiness has already been suggested in the sport science literature (Silva et al., 2013, 2014). Indeed, in the ecological dynamics approach, an individual's capacity to regulate behaviour is assumed to be supported by the perception of affordances (Passos, Araújo, & Davids, 2016). The concept of affordances here refers to possibilities for action that emerge from the interactions of an organism within a physical or social environment (Gibson, 1979). When a possibility for action is suddenly offered, this appears to the player to be a meaningful solution. Affordances are viewed as emerging from a direct perception of the performance's physical environment.

In its theoretical and methodological design, the study considered the players' subjective *own world* as a preliminary condition for describing the affordance. In this light, while described in the study using a quite divergent theoretical background, the empirical description of what it means to be attuned through a radar-like awareness, as observed in our data, fits well with the requirement of a perceptual readiness, as conveyed in affordance-based studies (Rietveld et al., 2016). Players tried to maintain an open perceptual readiness, waiting for a chance for action to become meaningful. In this way of enacting their world, players did not focalise on a specific variable, such as interpersonal distance or players' velocities, thus illustrating how local coupling to others can be achieved while not monitoring predetermined informational resources assumed to reveal expected opportunities for action. Considering that an important difference exists in terms of perceptual attitudes between being focalised on a given behavioural variable (e.g., a given player's trajectory or a given interval) and staying aware of the behavioural events that one can grasp in a nearby space (i.e., a radar-like readiness), it is noteworthy that most studies on social affordances are not clear on this distinction. While affordance concept described such a undirected awareness in animal species, studies conducted in sport with respect to the ecological dynamics approach have suggested that players (e.g., a rugby ball carrier) can improve their behavioural regulation by becoming attuned (i.e., focalised) to very specific spatiotemporal information, such as inter-player distance variability (Passos et al., 2011).

Stigmergy concept. The informational resources described also showed the possibility for players to regulate their behaviour based on their perception of the environment. In the past, individual regulation through the environment has been called stigmergy. Such a stigmergic type of regulation has also been investigated in sport science and called an *extra-personal coordination process* (Millar et al., 2013). Studies suggests the need to investigate the environment as a source of informational resources for agents seeking to coordinate in order to produce collective activity in sport (R'Kiouak et al., 2017). However, theoretical adaptations of the concept of stigmergy are necessary if we are to consider the environment a significant informational resource helping agents coordinate themselves in sport. Indeed, researchers suggest that a form of indirect coordination in sport is possible (Millar et al., 2013; R'Kiouak et al., 2017). However, the term stigmergy is used to designate coordination that occurs in response to traces of another agent that are immediately available and are perceptible as such a common and sensitive environment (i.e., these traces are to disappear). This definition differs from the definition of extra-personal coordination in that the sequential and permanent character of traces left in the environment is partially obscured. This reappropriation of the concept of stigmergy for the phenomenon of extra-personal coordination allows a heuristic approach to stigmergic coordination in sport. In short, regulation through the environment, as in the case of extra-personal coordination, has probably thus far been described only in rowing. The present project described regulation in relation to the ball as another form of extra-personal coordination. To conclude, stigmergic processes can be an effective, innate way of making collective behaviour emerge and of preserving multi-player coupling with key environmental events, such as those occurring in the ball area in the present football study setting.

Holoptism concept. The findings of the first study are in line with the present observations that suggest players can have a sense of the dynamics of global behaviour. It is important to consider that, unlike in the animal world, human collective behaviour itself can support co-interactors' adaptive activity and thus be considered a non-negligible informational resource. Such an ability to grasp the overall emergent states achieved through teamwork has been called holoptism (Bourbousson & Fortes-Bourbousson, 2016; Noubel, 2004). Holoptism is a concept which allows any participant to perceive in real time the manifestations of the other members of the group. Holoptism occurs when any team member grasps the dynamics of the whole interactive system and behaves in light of the given real-time joint effort perceived. To date, while being especially relevant to human behaviours, holoptism has not been investigated in sport. It must not be confounded with the perception of every team member's behaviour implied in the social system, which does not require a bird's-eye viewpoint.

Shared knowledge. To conclude, the team coordination process in the past has been assumed to be highly knowledge dependent (Blickensderfer et al., 2010). The knowledge that each team member can mobilise in the game is available so that he or she is still capable of adjusting activity based on expectations even if he or she does not necessarily grasp the current state of the game (i.e., relying on probabilistic events rather than situated informational resources). However, while social-cognitive theory postulates that most team coordination arises this way in expert teams, informational resources about knowledge were used only 5% of the time in our study.

Phenomenology as a priority

The phenomenological conviction displayed in the first study provided an empirical description that did not confine informational resources to any presupposed content. The present project therefore served to challenge existing studies and their assumptions about how team members coordinate in real time. In this light, the study proposed that teammates' active regulation of their behaviours was not predominantly knowledge-based but rather embedded in situational opportunities for action, while these opportunities could not be reduced to local-level affordances. Considering the actors' phenomenology thus helped us to propose a modelling free from bias regarding the content of informational resources supporting spatiotemporal adjustments.

The phenomenological approach has allowed the description of how ongoing collective behaviour and its dynamics are situated and managed online by agents, while being respectful of the singular, meaningful involvement of each team member. Contributing to a form of empirical micro-phenomenology (Kimmel, Hristova, & Kussmaul, 2018; Theureau, 2003), the enactivist approach to teamwork aims at describing the meaningful world of actors when being coupled to their naturalistic environment, including other team members. This form of phenomenology allows the production of descriptions of activity that are not limited to the third-person point of view as generated by the researcher's point of view (Varela & Shear, 1999). It has thus been introduced as a promising alternative to computationalism in psychology (Varela, 1988).

In sport science, such phenomenology has been fruitful in showing how qualitative descriptions of sport activities offer a counterbalance to current behavioural theories (Poizat et al., 2013). Regarding teamwork investigation, the approach has been mobilised to analyse the joint action of rowers (R'Kiouak et al., 2016), basketball players (Bourbousson et al., 2012), and table tennis teammates (Poizat et al., 2009).

Moreover, even if only the first study was designed according to the enactive approach, the elaboration of the simulation model in the second study was mainly based on the results of that first study. In this case, the social forces described were created according the local and global informational resources investigated in the first study. Some researchers have explained that combining qualitative and quantitative data could afford new possibilities for investigation (R'Kiouak et al., 2017; Seifert et al., 2016). In this project, the mix of phenomenological data and behavioural data was not considered in that sense, but phenomenology is considered in all the studies.

Combining phenomenology and physics to improve the power of the results

This project fulfilled a desire to describe the dynamics of collective behaviour and its phenomenology. Past research based on phenomenological data has suffered from a lack of statistics to improve the power of the results (Bourbousson et al., 2011; Bourbousson et al., 2012). Indeed, spatiotemporal patterns, coordination elaboration and functional variability cannot be fully explained with an exclusively qualitative approach (Bourbousson, 2015). Some qualitative methods exist to identify patterns of meaning in individual activity (Braun et al., 2016) or patterns of behaviour (Heath & Hindmarsh, 2002), but to show empirically that these patterns are *non-accidental* gains.

Based on the recommendations made by Bourbousson (2015), the present project attempted to design methodology that can reduce the lack of quantitative analysis. The point of criticism is not easy to operationalize while maintaining a fully enactive approach to social coupling, insofar as the second study uses mathematical modelling applied to quantitative data. In spite of these advances, the present project moved in the direction of a finer integrated of models and simulated a physical model resulting from the theory of dynamic systems. In this way, the design of the study integrated data in the first-person by mathematizing the intrinsic data of the first study before modelling them. This model gave the opportunity to control all parameters. By switching only the parameter associated with the intrinsic data, it was possible to assume that the changes in terms of collective patterns were the consequences of the altered intrinsic parameter (i.e., local or global adjustment). Even if this study does not afford powerful inferential statistics, the use of a simulation study improves the power of the intrinsic data.

Simulation as innovative method to investigate teamwork

Among the researchers on teamwork, a growing interest in multi-agent modelling and simulation has arisen. Teamwork has been considered as necessary for humans notably in the collaborative skills but also for supporting decision making, for sharing information and for building coherent teams. Collective behaviour modelling is investing in many scientific fields, such as cognitive science, ethology , and distributed artificial intelligence (Fan & Yen, 2004). Most of the research on multi-agents systems and teams has been investigated in the field of robotics (Gao, Cummings, & Solovey, 2014). Seconde study of this project was based on the idea that collective behaviour in football has something in common with multi-agent systems and the belief that that the field of sport science should probably invest in this scientific methodology.

Most of the current collective behaviour simulation has been inspired by simple local rules of interaction suggested in ethology research. The second study investigated the level of the emergence of collective human behaviour, but other fields have been investigated extensively. Ethology in particular has studied the emergence of collective behaviour. The collective behaviour of animal societies has been extensively investigated (Deneubourg & Goss, 1989; Perna et al., 2012), and the results have contributed to the implementation of functional interaction rules in multi-robot systems. Researchers explained how to control spatial configuration by explaining that a robot can contribute to building collective behaviour based on relatively simple interactions and behavioural rules. Robots in these systems are currently able to cooperate (Detrain, Deneubourg, Boissy, Pham-Delegue, & Baudoin, 2009), communicate or interact through the changes they impose on their environment. Each robot is equipped with a transmitter and a receiver: its position, its decision and its movement will influence the behaviour of its fellows. Independent of human control, several autonomous robots are thus able to manipulate objects in a coordinated way and to group previously randomly dispersed objects without a pre-established plan (Martinoli, Theraulaz, & Deneubourg, 2002).

Promising research projects could be built that investigate the benefits of distinct modes of regulation of individual agents' contributions to teamwork, as do some projects based on monitoring team states. The second study, by widening our knowledge of informational resources, can perhaps help to make the collective self-organisation of robots more efficient. In other words, several robots arranged according to rules such as those for local interaction (i.e., rules inspired by insect societies) could engage in collective behaviour that is close to what is already done in this type of system (Martinoli et al, 2002) but which would ultimately be more fragile than that of robot collectives organised around global interaction rules. The implementation of a global regulation mode is more complex, as it requires a global perception of coordination, and thus requires having some robots, if not all, specialized in the perception and actualization of this current form. The issue of specific roles of some agents has not been addressed in our work. However, the functioning of animal groups points to the place of leadership, or at least to some specialized members. Within a group, the hierarchical position often determines its access order. In other words, regulation is no longer done in a near space but in the face of an individual considered as a particular individual. This type of approach differentiating the coordinating individuals recently gave very convincing results, which were published in the magazine Science by the Nagpal team (Rubenstein, Cornejo, & Nagpal, 2014), and could be a source for development of our experimental design.

The complementary study elaborated an experimental design. In sport science, the construction of an experimental paradigm for studying collective behaviours and their modes of regulation remains a path to explore. However, this type of methodology could allow the testing of various parameters in the elaboration of collective behaviour.

IMPLICATIONS OF FINDINGS FOR TEAM SPORT

Talent wins games, but teamwork and intelligence wins championships. Michael Jordan (2018)

In a complex collective activity, players wait for guidance on what their behaviour has influenced. It is the same for the coach, who, in the verbal exchanges with the players, addresses them with instructions essentially for an active and voluntary commitment on their part in collective training and match situations. This research contributed in a certain way to improving team performance. The studies mainly gave fundamental findings, however, these could also afford the possibility for a coach to obtain new ideas and innovative tips to increase the performance of the collective behaviour of their team. A coach from a French football team explained that to know when the team attack players should increase the surface area and the team defense players should reduce the surface area, the players must have a global perception of the game. From this idea, this project showed that players use information based on the global level of perception, and the adjustment of players based on informational resources involving changes in the spatiotemporal collective patterns and interaction rules could control those informational resources and the related adjustment. These results provide input for the coach.

Players' perceptions. A coach should be able to teach players how to develop the various forms of perception. The teaching of perception could be helped by interaction rules that involve specific perception. Coaches could be inspired by the various informational resources mobilised by football players when adjusting their displacement on the field, regarding the spatiotemporal needs. In light of the global regulation exemplified here, coaches could develop practices offering spacing large enough so that the density of players becomes salient (i.e., free space and densified space) and call players to use the global perception of team states. To complement this training approach, coaches could develop practices using small-sided games, implying short inter-player distances and time pressure, which are supposed to call for local awareness development. In terms of mental training, practitioners could invent exercises to help players make a switch in mental attitudes and perception (e.g., from broad unfocused to directed awareness and from local to global awareness). Players, nevertheless, should understand what their role is, and they should know how to interact with other players by knowing where those other players are on the field and how those players are connected to others. The first study aimed at providing knowledge on what players are focused on when they contribute to the collective behaviour. For this reason, the study affords some practical considerations.

Football as a complex behaviour. A football match is a systemic confrontation between two systems; teams that have the same structure attempt to create chaos in the opposing organisation (Davids, Araújo, & Shuttleworth, 2005). The systems are necessarily connected to each other, and the big question is how the systems adapt to each other and to the constraints of the environment. Their great strength, and at the same time their weakness, is that they are subject to permanent regulation of those who constitute them. There is a delicate balance between the identity of the system and the constraints, and thus one has basically a dynamic evolution of the system. Our scientific project provided new knowledge associated to this description. It is classically demonstrated in complex systems that small changes in one context may produce significant qualitative changes in a team's behaviour (Couzin et al., 2002). The individual changes described by various adjustments result in specific collective patterns. Coaches want specific collective organisation without knowing how to obtain it; knowledge about local and global adjustments could facilitate the construction of this collective behaviour. It is important for coaches to understand that the stability of the team (i.e., the system) produces behaviours which are more or less predictable, and this collective behaviour has implications for individual and team performance. Training should include situations with abundant informational resources that develop various modes of adjustment and thus result in an improved team organisation. Coaches should be a designer rather than basic instructors.

Emergence in football. The challenge is not to provide answers to training and coaching questions for coaches, but to discuss what this approach could possibly afford to football performance. Investigating the collective dimension of the activity, especially through the processes of emergence, shows that it is possible to organise collective behaviour at the spatiotemporal level on the basis of a generic guideline applicable to each level (i.e., local or global) and to provide guidance on how to interact with partners. This proposal echoes existing training practices, such as those advocated independently of these considerations. Other studies have confirmed that indicators such as the distance of the players from the ball, the surface that the team has developed, and the distance of the players from each other are interesting indicators to describe what members of a team, a collective, produce together. And these could be used more widely in the analysis of team sports. These indicators could also be considered further to become tools for learning collective performance. Finally, the phenomena of top-down and bottom-up causality can be a new axis of reflection for the training of the collective. Another interesting avenue might be to organise training through inter-organisational interactions, sometimes focusing on dyadic work and sometimes on the team as a unit.

To conclude, current football is really open to big data with an orientation toward the evaluation of individual characteristics (e.g., technical and physical). This orientation toward big data and all the associated statistics allows for improving performance. However, all the treatment or focus is on one player and not on the collective behaviour. Our project aims to create links between individual performance and its consequences in the collective behaviour. All the individual changes in understanding would help in bringing more practical applications for real-world scenarios and coaches. Identifying the different individual changes that may constrain the system may help in developing a specific strategy to avoid or to explore the weakness and strengths of a team.

CONCLUSION AND PERSPECTIVES

This entire project has highlighted the lack of consideration for the individual regulation of an agent's activities in sport sciences. Our overall results, nonetheless, describe individual regulation as a key object to understanding interpersonal coordination processes. The studies have also made methodological and empirical contributions which benefit collective behaviour research, especially in football. In this project, we attempted to understand the effect of regulation on collective behaviour, first by investigating the informational resources supporting players' activities in football; second, by modelling collective behaviour and testing hypotheses about various adjustment modalities; and finally, by attempting to control human regulation based on interaction rules when participants contribute to collective behaviour.

The objective of the future project should be to identify more links between informational resources and individual adjustment. For instance, how do the various informational resources translate in terms of empirical adjustment? The adjustment could be at the level of the trajectory of individuals: What is the impact on the trajectory and the speed? One can imagine that the local mode answers questions of distance, maintenance or change with respect to an individual. One can also imagine that the global adjustment responds to a maintenance or change of the surface developed by the team. To know these answers, there is a need to document various hypotheses.

Short term. The present project has attempted to bridge some gaps. However, some questions remain unresolved. For example, the question of the different profiles of players (i.e., defender, midfielder and attacker) has not been studied. The numbers of players and the size of the field have not been considered in assessing the possibility of globally regulating the individual's activity to others. Moreover, the condition of production and the requirement for each informational resource need to be investigated to understand when one is more relevant than others.

Medium term. This project has studied the correlation between individual regulation and the consequences for collective behaviour. A less common investigation, but equally important, should focus on the relation between collective behaviour and individual behaviour. This approach could give a global-to-local analysis. Here, the goal would be to observe patterns at the global level and use them to infer properties of agents and their interactions at the local level. This study would provide new knowledge about top-down causality, whereas the present project has described bottom-up causality.
We should not put in contradiction the individual activity and the collective behaviour. The individual activity will be all the more powerful when the collective is effective. In this case, each must draw on the quintessence of its quality.

Long term. This is another story

Complementary Contents

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APPENDICES

This part presents all the appendices associated to the methodological steps that have been described in the methods sections.

The first appendix present an example of self-confontration verbatim.

The second appendix present the process conducted for the thematic analysis.

The third appendix present the codes elaborated in the second study.

APPENDIX 1 - SELF CONFRONTATION VERBATIM

Transcription. Following the observed football sequences, the players were interviewed in order to collect, the experience of their activity. Table 1 shows verbatim excerpts illustrating the transcriptions obtained from the verbalizations collected in the self-confrontation interview. An example of one single player

Time	Verbatim Player 1
0'09	**Chercheur** : Le ballon est sur la gauche, c'est quoi ton rôle là ? ***Player 1*** *: Je ne sais pas pourquoi je suis la, quand Fernand sort avec le ballon comme ça. Sur cette position je pense qu'on avait changé de place entre temps normalement c'est Adrien qui est censé être plus bas. Fernand doit partir avec le ballon et moi je le remplace dans la défense.* **Chercheur** : Tu regarde quoi ? ***Player 1*** *: Oui je suis focus sur fernand, soit je propose pour avoir le ballon soit je pars pour le remplacé s'il monte avec le ballon.*
0'19	**Chercheur** : c'est quoi ton rôle ? ***Player 1*** *: Remonter avec le bloc et essayer avec Adrien de trouver une place là* **Chercheur** : Tu as une vue d'ensemble du terrain ? ***Player 1*** *: Oui je vois toute l'équipe, tout le milieu surtout et où sont placés leur joueur donc on va essayer de se placer*
0'25	**Chercheur** : tu es concerné là ? ***Player 1*** *: Non, je regarde ce qui se passe devant*
0'31	**Chercheur** : récupération des bleus, tu t'organises comment ? ***Player 1*** *: D'être du côté ou le ballon va sortir et je vais être obligé d'être avec Adrien, d'être avec Adrien, si Adrien reste la je vais devoir sortir et si Adrien monte je vais couper.*
0'33	**Chercheur** : Là c'est porteur de balle et Adrien sur lequel tu t'appuies ? ***Player 1*** *: C'est ça, je sais que le porteur de balle vu qu'il est là il va aller sur le côté et moi mon déplacement ça sera que par rapport à Adrien. Si Adrien restait la ça allait être moi qui était obligé de sortir.*

APPENDIX 2 - THEMATIC ANALYSIS

Behavioural description & participants singularly reported their experience of the game dynamics. Example with 2 players.

Time	Time code		Verbatim Player 1	Verbatim Player 2
0’09	**1**	**La balle est dans le rond central, le numéro 10 rouge à la balle.**	**Chercheur** : Le ballon est sur la gauche, c’est quoi ton rôle là ? **Joueur 1** : Je ne sais pas pourquoi je suis là, quand Fernand sort avec le ballon comme ça. Sur cette position je pense qu’on avait changé de place entre temps normalement c’est Adrien qui est censé être plus bas. Fernand doit partir avec le ballon et moi je le remplace dans la défense. **Chercheur** : Tu regardes quoi ? **Player 1** : Oui je suis focus sur fernand, soit je propose pour avoir le ballon soit je pars pour le remplacé s’il monte avec le ballon.	
0’11	**2**			
0’13	**3**	**La balle est en défense, c’ est le défenseur central rouge numéro 5 qui a la balle**		**Chercheur :** A ce moment tu es concentré sur quoi ? **Player 2 :** Si Fernand est bien orienté il y de l’espace entre lui et moi je suis tout seul , il est déjà conditionné à la mettre la bas

0’19	**4**	**Un grand ballon est envoyé devant par le defenseur central rouge numéro 4.**	**Chercheur** : Tu es focus sur quoi la ? **Joueur 1** : Remonter avec le bloc et essayer avec Adrien de trouver une place là **Chercheur** : Tu as une vue sur ? **Joueur 1** : je vois toute l’équipe, tout le milieu surtout et où sont placés leur joueur donc on va essayer de se placer	**Chercheur :** alors la tu penses à qui ? a quoi ? **Player 2 :** je me suis orienté , en temps que milieu de terrain, je viens pas dos au jeu, le temps de son contrôle (partenaire porteur de balle en défense), je suis deja orienté alors il me la donne je m’oriente et je vais vers l’avant j’avais plusieurs possibilité, je la mets coté systémtiquement...alors que regarde Milan il est tout seul **Chercheur:** Finalement qu'en Karyl il a la balle? tu vois qui ou quoi ? **Player 2 :** Je voyais Karyl, je pensais qu'il allais me la mettre, il met un long ballon, je dis encore un long ballon, il faut partir et many est la, il faut aller accompagner
0’25	**5**	**Le ballon est en attaque Il y a cafouillage entre les rouge et les bleux**	**Chercheur** : tu es concerné là ? **Player 1** : Non, je regarde ce qui se passe devant	**Chercheur :** a ce moment la ? **Player 2 :** ils ont ballon.. c’est en model « je pense qu’a ma gueule je pense qu’a marquer » ils sont deux ils ont moyen de combiné pour marquer, et ca été que ca … a un moment donné pour nous c’est frustrant les millieux de terrains parce que qu’on est sensé partir apporter et quand on apporte et que eux il mettent un long ballon que nous on va accompagné
0’31	**6**	**Les bleux récupèrent la balle, le numéro 9 à la balle il remonte vers le milieu du terrain**	**Chercheur** : récupération des bleus, tu t’organises comment ? **Player 1** : D’être du côté ou le ballon va sortir et je vais être obligé d’être avec Adrien, d’être avec Adrien, si Adrien reste la je vais devoir sortir et si Adrien monte je vais couper.	**Chercheur:** Au moment du cafouillage la est ce que tu te remets dedans ? **Player 2 :** ouai je suis la j’attends que ca vienne je vois qu’on est 4 je sais que many il était pas bien il a recu un coup donc moi je reste, la je regarde que le ballon, que le ballon et le joueur, le joueur adverse fait le frainer empecher la contre attaque
0’33	**7**	**Le numéro 10 bleu à la balle sur le coté près de la ligne médiane**	**Chercheur** : Là tu t’appuies ? **Player 1** : C’est ça, je sais que le porteur de balle vu qu’il est là il va aller sur le côté et moi mon déplacement ça sera que par rapport à Adrien. Si Adrien restait la ca allait être moi qui était obligé de sortir.	**Chercheur:** donc la il fait la passe ? qu'est ce que tu te dis ? **Player 2:** Je vais sur le joueur par ce que… ba il est la le milieu droit (partenaire située en attaque), et la l’attaquant regarde ou ils sont , des qu'il y a une occasion pour nous il y a pas de retour, desfois on va récupérer un ballon et il va être hors jeu, on ne peut pas jouer avec eux, par ce que il y a leur action , ils ont fait leur truc et ils pensent pas à la suite

Delineating MUAs as identifiable within each participant's experience report

Total code	Player Code	Player 1
1	1	Il voit fernand qui sort le ballon
2	4	Il remonte le bloc avec adrien son partenaire proche et il avec lui de trouve une place, il voit toute l'équipe et tout le milieu surtout et où sont placées leur joueur.
3	5	Il regarde ce qu'il se passe devant
4	6	Il se met du coté ou le ballon va sortir quand les adversaires attaques, il est obligé avec adrien
5	7	Il prévient Karyl son défenseur central qu'il lui laisse un joueur, il va sur un autre joueur, il fait ca par rapport au appel, au joueur, par ce que si il reste sur cet adversaire et l'autre adversaire va rester seul et il va pouvoir avoir la balle, le deuxième ballon ne doit pas être bleu
6	8	Il voit ce qu'il se passe, si l'adversaire se met face à Karyl alors il anticipe une passe en retrait, soir Karyl se fait dribbble et il coupe, "je dois être plus proche"
…	…	…
64	107	son partenaire a bien suvit l'action, son partenaire doit lui laisser le joueur adverse
Times Code	Joueur Code	Player 2
65	3	Il sait que son partenaire defenseur proche est conditionné pour balancer un bon ballon
66	4	Le numéro 7 adverse proche ne le presse pas le porteur de balle, Il regarde le porteur de balle
67	5	Les deux attaquants ont moyens de faire quelque chose, il sont 2, il y a long ballon il faut accompagner
68	6	Il est en place il attend que ca vienne, il voit qu'ils sont 4 (partenaires) , il s'est qu'un de ses partenaires ne va pas très bien donc il reste, il est focus sur le PDB et le ballon
69	7	Il voit son partenaire attaquant mal repositionner pour défendre, il va sur le PDB adverse
70	8	Il revient a sa place, le long ballon est dangereux
71	9	il lève a main en disanrt jouer a son gardien, il est dans l'interval entre 2 adversaires, Il sont a 3 contre 1,finalement toute l'équipe sort
…	…	…
625	107	Son partenaire est parti (many) , dans sa vision de l'adversaire, il voit qu'il va aller sur le coté

Coding SIRs supporting each MUA

Code	codes	SIRs supporting each MUA
n	Player 1	Singular informational resource
1	1	Perception du porteur de balle qui est un coéquipier
2	4	Perception du bloc avec perception du partenaire le plus proche
3	5	Perception générale de ce qu'il se passe autour du ballon sans focus précis
4	6	Perceptions des attaquants adverses avec la balle et du partenaire le plus proche
5	7	Perception d'un adversaire unique non porteur de balle
6	8	Perception de ce qu'il se passe autour du ballon
…	…	…
64	107	…
	Player 2	Singular informational resource
65	3	Perception d'un partenaire unique
66	4	Perception d'un partenaire porteur de balle
67	5	Perception des attaquants adverses
68	6	Perception du porteur de balle adverse et des partneaires à coté
69	7	Perception d'un partenaire et gestion d'un adversaire
70	8	Positionnement sur la base de ces connaissances
71	9	Perception de l'équipe qui sort et d'un petit grouoe de joueur
…	…	…
625	107	…

Developing themes through clustering investigating informational resources

N	First-order theme
1	Perception globale de l'état spatio-temporel de son équipe
2	Perception d'une petite unité collective (e.g., les défenseurs; les attaquants)
3	Perception globale du jeu laissant apparaître une surface libre offrant une opportunité d'action
4	Perception globale du jeu révélant une forte densité de joueurs dans un espace
5	Jugement sur la configuration du rapport de force instantané entre les deux équipes

6	Perception simultanée du mouvement général (e.g., mouvement général des joueurs, espaces libres..) et du comportement d'un agent unique
7	Perception simultanée d'un agent et de l'état spatiotemporel d'une petite unité collective
8	Perception simultanée des comportements de deux agents uniques distants entre eux
9	Perception simultanée de la zone de jeu lointaine et des événements se produisant dans l'espace proche

10	Focalisation sur la trajectoire/déplacement du ballon
11	Perception des comportements autour du ballon

12	Focalisation sur les attitudes d'un partenaire PB
13	Focalisation sur les attitudes manifestes du PB adverse
14	Focalisation sur le déplacement d'un partenaire NPB
15	Focalisation sur le déplacement d'un adversaire NPB
16	Perception d'une distance interpersonnelle

17	Mobilisation de connaissances sur le jeu permettant d'inférer des déplacements associés à la tactique
18	Mobilisation de connaissances sur sa propre équipe permettant d'inférer les déplacements de ses partenaires

19	Perception flottante, non focalisée de l'ensemble de l'espace proche (e.g balle, joueur, espace, distance)

Elaboration of the second-order theme

N	First-order theme		Second-order theme
1	Perception globale de l'état spatio-temporel de son équipe	1	Perception du comportement spatiotemporel d'une unité sociale (composée d'un nombre plus ou moins grand de joueurs)
2	Perception d'une petite unité collective (e.g., les défenseurs; les attaquants)		
3	Perception globale du jeu laissant apparaître une surface libre offrant une opportunité d'action	2	Perception de l'adéquation de l'utilisation de l'espace par les équipes
4	Perception globale du jeu révélant une forte densité de joueurs dans un espace		
5	Jugement sur la configuration du rapport de force instantané entre les deux équipes		
6	Perception simultanée du mouvement général (e.g., mouvement général des joueurs, espaces libres..) et du comportement d'un agent unique	3	Perception simultanée d'un agent unique et d'une situation plus global
7	Perception simultanée d'un agent et de l'état spatiotemporel d'une petite unité collective		
8	Perception simultanée des comportements de deux agents uniques distants entre eux	4	Perception simultannée d'une double focalisations
9	Perception simultanée de la zone de jeu lointaine et des événements se produisant dans l'espace proche	5	Perception simultanée non focalisé de l'espace proche et d'une zone de jeu plus lointaine
10	Focalisation sur la trajectoire/déplacement du ballon	6	Perception de la zone où se passe le jeu
11	Perception des comportements autour du ballon		
12	Focalisation sur les attitudes d'un partenaire PB	7	Focalisation sur les attitudes et les intentions manifestes d'un joueur
13	Focalisation sur les attitudes manifestes du PB adverse		
14	Focalisation sur le déplacement d'un partenaire NPB	8	Focalisation sur la trajectoire de déplacement d'un joueur
15	Focalisation sur le déplacement d'un adversaire NPB		
16	Perception d'une distance inter-personelle	9	Perception de la taille d'un intervalle inter-joueurs
17	Mobilisation de connaissances sur le jeu permettant d'inférer des déplacements associés à la tactique	10	Mobilisation de connaissances préalables suggérant les évènements supposés se produire
18	Mobilisation de connaissances sur sa propre équipe permettant d'inférer les déplacements de ses partenaires		
19	Perception flottante, non focalisée de l'ensemble de l'espace proche (e.g balle, joueur, espace, distance)	11	Perception flottante de l'ensemble de l'espace proche

Elaboration of the third-order theme

	Second-order theme	N	Third-order themes
1	Perception du comportement spatiotemporel d'une unité sociale (composée d'un nombre plus ou moins grand de joueurs)	1	Ancrage de l'activité du joueur dans la perception de la **configuration globale des déplacements des joueurs**
2	Perception de l'adéquation de l'utilisation de l'espace par les équipes		
3	Perception simultanée d'un agent unique et d'une situation plus global	2	Ancrage de l'activité du joueur dans la perception simultanée du comportement d'un agent unique et d'une forme spatiotemporelle plus globale
4	Perception simultannée d'une double focalisations		
5	Perception simultanée non focalisé de l'espace proche et d'une zone de jeu plus lointaine		
6	Perception de la zone où se passe le jeu	3	Ancrage de l'activité du joueur dans la perception de **la zone où se passe le jeu**
7	Focalisation sur les attitudes et les intentions manifestes d'un joueur	4	Ancrage de l'activité du joueur dans la perception du comportement d'**un agent unique**
8	Focalisation sur la trajectoire de déplacement d'un joueur		
9	Perception de la taille d'un intervalle inter-joueurs		
10	Mobilisation de connaissances préalables suggérant les évènements supposés se produire	5	Ancrage de l'activité du joueur dans **des connaissances préalablement construites suggérant** les évènements supposés se produire
11	Perception flottante de l'ensemble de l'espace proche	6	Ancrage de l'activité du joueurs dans la perception flottante de l'espace proche

Elaboration of the table : Frequency and intraclass percentage of SIRs used by the team members during a match.

Time code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	…	107
Player 1	3			13	12	16	11		1		12		12			10	16	…	16
Player 2			16	7	11	11	8	10	1	10	12	13	12	12		2	17	…	18
Player 3	12	14	11	11	12	2	6	6	16	12	16		12	16	4		12	…	15
Player 4	14	11		18	14	17	15	15	10	7	9		14	17	11	19	2	…	15
Player 5	2			17	11		6	11	1			1	12	10		18	10	…	2
Player 6	2	16		14	17	6	10	10	14	14	12	9	9	12	12	3	3	…	
Player 7	19	12		9	10	16	17		18		12	8	12	3	12	2	7	…	2
Player 8	7	2		5	7	9	14		7	9	2	11		3			14	…	
Player 9	16	16	7	1	3		9	15	2		17	11		18			7	…	2
Joueur 10	12			1	11	7	7	11	16		19	17	3	3		15	5	…	11

APPENDIX 3 - CODES

Input files

A file foot.c which generate the data positions of each agent. This section only present the comments without include the code itself.

```
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <time.h>
#include <float.h>
#include "tools_foot_v6_4.h"

int
main(void)
{
/* Declaration des variables */
        /* entiers necessaires */
        /* diverses coordonnees  des joueurs */
        /* ballon */
        /* regulation*/
        /* constantes */
        /* pour gerer les nombres aleatoires */
        /* des intermediaires de calcul */
        /* pour les centres de masse */
        /* pour les passes */
        /* les fichiers */

/* Initialisation des variables */
 /* allocation de l'espace memoire */
 /* lecture des parametres */
/* calcule le terme de diffusion dans l'equation des forces sociales */
/* initialisation des racines du generateur de nombres aleatoires */
/* limite du terrain avec pour origine le centre */
/* Initialisation pour la ligne de hors-jeu */
/* Initialisation des positions */
/* enregistrement */
```

At this stage all agents have one position on the field. This represent t = 0.

```
  /* boucle sur le temps*/
        /* Trajectoire du ballon, interaction avec porteur et defenseur et passe */
```

```
        /* Echange d'equipe s'il y a une sortie de jeu ou prise de balle */
        /* recherche d'un coequipier libre */
        /* vrai numero du coequipier avec qui faire la passe les tableaux angle et dist ne sont
        pas tries sur les attaquants */
        /* choix de l'angle parmi amin et amax l'angle moyen */
        /* Passe */
         /* ballon : trajectoire rectiligne a la vitesse vb ex et ey ne change pas, calcul du pas
        suivant */
        /* ballon porte sans passe ou apres prise de balle */
        /* le porteur va au but */ /* en evitant les defenseurs */
        /* pour chacun des attaquants : calcul des forces */
        /* contrainte de zone */
        /* eviter les chocs avec les voisins */
        /* Regulation */
        //Redimmensionnement

}/*fin boucle temps */

/* Liberation de l'espace memoire */
```

A file metric.c which calculate all the metrics from the position data

```
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <string.h>
#include "tools_metric.h"

int main()
 {
  FILE* positions_1 = NULL;
  FILE* positions_2 = NULL;
  FILE* metriques = NULL;
  int nb_joueurs = 20;
  double t_max = 17999.;
  double *x_1, *y_1;
  double *x_2, *y_2;
  double bx_1, by_1, bx_2, by_2;
  double si_barycentre_1, si_barycentre_2;
  double etirement_x_1, etirement_y_1, etirement_x_2, etirement_y_2;
  double surf_1, surf_2;
```

```
 double std_stretch_1, std_stretch_2;
 int ball_1;
 int ball_2;
 double rapport_centroid;
 double phase_rel;

char temps [] = "Temps";
char balle_1 [] = "Ball_1";
char balle_2 [] = "Ball_2";

char centx_1 [] = "Centroid_x_1";
char centy_1 [] = "Centroid_y_1";
char centx_2 [] = "Centroid_x_2";
char centy_2 [] = "Centroid_y_2";
char si_1 [] = "Stretch_1";
char si_2 [] = "Stretch_2";
char eti_x_1 [] = "Spread_x_1";
char eti_x_2 [] = "Spread_x_2";
char eti_y_1 [] = "Spread_y_1";
char eti_y_2 [] = "Spread_y_2";
char surface_1 [] = "Surface_1";
char surface_2 [] = "Surface_2";

char si_balle_1 []= "Stretch_ball_1";
char si_balle_2 [] = "Stretch_ball_2";
char centy_12 [] = "Rapport_Centroid(y)";
char std_istretch_1 [] = "Variation_Stretch_1";
char std_istretch_2 [] = "Variation_Stretch_2";

char phase_rela [] = "Phase_relative";


 x_1=(double *)malloc(nb_joueurs/2*sizeof(double));
 y_1=(double *)malloc(nb_joueurs/2*sizeof(double));
 x_2=(double *)malloc(nb_joueurs/2*sizeof(double));
 y_2=(double *)malloc(nb_joueurs/2*sizeof(double));

 metriques = fopen("metriques.txt", "w");

 fprintf(metriques, "%s %s %s %s %s %s %s %s \n",
```

```
temps,balle_1, centx_1, centy_1, eti_x_1, eti_y_1, surface_1, si_1);

positions_1 = fopen("trajectoires_1.dat", "r");
positions_2 = fopen("trajectoires_2.dat", "r");

for (double t = 0; t < t_max ; t++)
{
  //printf("%d\n", t);
  for (int i = 0; i < nb_joueurs ; i++){
    if (i < nb_joueurs/2) {
      fscanf(positions_1, "%*lg %lg %lg %*g %*g %d", &x_1[i], &y_1[i], &ball_1);
    } else {
      fscanf(positions_2, "%*lg %lg %lg %*g %*g %d", &x_2[i-nb_joueurs/2],
      &y_2[i-nb_joueurs/2], &ball_2);
    }
  }

  //Calcul des métriques
  bx_1 = moyenne(nb_joueurs/2, x_1);
  bx_2 = moyenne(nb_joueurs/2, x_2);
  by_1 = moyenne(nb_joueurs/2, y_1);
  by_2 = moyenne(nb_joueurs/2, y_2);
  si_barycentre_1 = stretch_index(nb_joueurs/2, x_1, y_1, bx_1, by_1);
  si_barycentre_2 = stretch_index(nb_joueurs/2, x_2, y_2, bx_2, by_2);
  //si_balle_1 = stretch_index(nb_joueurs/2, *x_1, *y_1, x_ball, y_ball);
  //si_balle_2 = stretch_index(nb_joueurs/2, *x_2, *y_2, x_ball, y_ball);
  etirement_x_1 = etirement(nb_joueurs/2, x_1);
  etirement_x_2 = etirement(nb_joueurs/2, x_2);
  etirement_y_1 = etirement(nb_joueurs/2, y_1);
  etirement_y_2 = etirement(nb_joueurs/2, y_2);
  surf_1 = surface_area(nb_joueurs/2, x_1, y_1, bx_1, by_1);
  surf_2 = surface_area(nb_joueurs/2, x_2, y_2, bx_2, by_2);



//std_stretch_1 = v_stretch_index(nb_joueurs/2, x_1, y_1, bx_1, by_1);
//std_stretch_2 = v_stretch_index(nb_joueurs/2, x_2, y_2, bx_2, by_2);

//  rapport_centroid = by_1 - by_2;
//  phase_rel = relative_phase (bx_1, bx_2, by_1, by_2);
```

```
 if (ball_1 <2)
 {
  fprintf(metriques, "%g %d %g %g %g %g %g %g \n",
  t,ball_1, bx_1, by_1, etirement_x_1, etirement_y_1, surf_1, si_barycentre_1);
 }
}
 fclose(positions_1);
 fclose(positions_2);
 fclose(metriques);
 return 0;
}
```

A file multi.sh which generate a simulation number chosen

```
!/bin/bash
echo "Nombre de simulations ?"
read N

gcc -c tools_foot_v6_4.c -o tools_foot_v6_4.o
gcc -c foot_v6_4.c -o foot_v6_4.o
gcc foot_v6_4.o tools_foot_v6_4.o -o foot_v6_4 -lm

gcc -c metric.c -o metric.o
gcc -c tools_metric.c -o tools_metric.o
gcc metric.o tools_metric.o -o metric -lm

mkdir ./resultats_$N
echo 'Series temporelles des metriques pour $N simulations\n' >
./resultats_$N/metric_series.txt
#echo 'Moyenne des metriques pour chaque simulation\n' > ./resultats_$N/metric_moy.txt

for (( i = 0 ; i < N ; i++ ))
do
 ./foot_v6_4
 ./metric
 cat metriques.txt >> ./resultats_$N/metric_series.txt
 echo '\n\n' >> ./resultats_$N/metric_series.txt
 #cat moy_metriques.txt >> ./resultats_N/metric_moy.txt
 #echo '\n' >> ./resultats_N/metric_moy.txt
done
exit 0;
```

A file Param.data which initialised all the parameter

```
2 0.05 18000
80 0.3 1 0.2 3
3 3 0.5 15
2.0 0.2
20000.0 40000. 20000.
100000.0 8000.0
1000000. 1000000.
1 0
30. 5. 20.
50
1 35
80  120
# r0 deltat tmax
# masse=80kg rc masse_d tau_choix tau_acc
# v0=11km/h vlimite veps vb
# diffusion proba
# Ub Uc Uz
# Ud Ue
# Ulocal Uglobal
# coef_local coef_global
# ldx ldy levit
# coef_but
# r1 r2
# lx=80m ly=120m
# xz yz lxz lyz

 15    25   20   20
-15    25   20   20
-10     0   10   10
 10     0   10   10
-20     0   10   25
 20     0   10   25
-20   -20    5   10
 20   -20    5   10
 -5   -25    5    5
  5   -25    5    5
 15   -25   20   20
-15   -25   20   20
-10     0   10   10
 10     0   10   10
-20     0   10   25
 20     0   10   25
 -5    25    5   10
  5    25    5   10
-20    20    5    5
 20    20    5    5
# pour chacun des joueurs en commencant par le porteur
```

Compile

```
/* Compilation : ATTENTION 3 étapes
gcc generate_tactics.c
./a.out
gcc -c tools_foot_v6_4.c -o tools_foot_v6_4.o
gcc -c foot_v6_4.c -o foot_v6_4.o
gcc foot_v6_4.o  tools_foot_v6_4.o -o foot_v6_4 -lm
./foot_v6_4
gcc -c metric.c -o metric.o
gcc -c tools_metric.c -o tools_metric.o
gcc metric.o  tools_metric.o -o metric -lm
./metric
*/
```

Output files

A trajectory file with all the position (x,y) and speed of all the agents.

Example for one team at the time 0.

Player	Time	Position (x)	Position (y)	Speed (x)	Speed (y)	Ball
1	0	15	-5	0	0	0
2	0	-15	-5	0	0	1
3	0	-10	-30	0	0	1
4	0	10	-30	0	0	1
5	0	-20	-30	0	0	1
6	0	20	-30	0	0	1
7	0	-20	-50	0	0	1
8	0	20	-50	0	0	1
9	0	-5	-55	0	0	1
10	0	5	-55	0	0	1

A file constant.dat to check if all the energies are in the same level

Distances

lx=40, ly=60

rc=0.15

defense lx=15, ly=2.5

attaque levit=10

r1=0.5, r2=17.5

Energies

E_cinétique=0.225, U_but=0.9375

U_bords=0.15625, U_ccollision=0.3125, U_zones=0.15625

U_défense=62.5, U_évitement=5, Ulj=625, Uglob=625

Vitesses

v0=0.075, vb=0.375, vmax=0.225

A file metric.txt which present the results.Illustration of the results for the local adjustment modalities. The mean of the metrics for each simulation.

Local	STD centroid x	Centroid_y_1	Spread_x_1	Spread_y_1	Surface_1	Stretch_1	Ratio_L/W
1	10,37551948	-16,10517284	50,48123514	53,3805987	1564,76111	21,3076181	1,112198872
2	9,291732324	-15,0383595	50,67927408	53,0717539	1596,47197	21,347704	1,118676671
3	9,642517713	-13,41619572	50,43069322	56,7524503	1693,57918	22,1115904	1,172654118
4	9,226163611	-12,78471032	47,95899773	54,1088365	1549,77343	21,2046684	1,198158887
5	9,878916951	-14,18617197	48,68200957	56,9184903	1599,20516	21,5234993	1,219028381
6	8,330995593	-19,30801534	48,33928928	54,7965357	1574,00915	21,2142463	1,221333046
7	11,68265904	-14,58638289	49,40156067	52,9007181	1595,39502	21,2968414	1,122884881
8	10,1345648	-18,49884259	50,04008255	52,3753971	1558,23596	21,4360637	1,128290313
9	9,549180101	-19,33142764	50,30028115	52,4720725	1541,44466	21,0024928	1,103732895
10	10,53999848	-15,39200447	50,6917504	53,9857137	1654,074	21,3712152	1,122185836
11	7,905511603	-14,41583043	48,47029831	55,6984786	1551,35649	21,1851341	1,212413776
12	9,985658935	-19,58549642	48,03709494	52,351455	1497,94057	20,785049	1,165671804
13	8,466630228	-15,60119132	48,96598372	55,6044444	1549,49021	21,3471288	1,199367201
14	9,876329645	-16,65751297	48,2878305	56,1870118	1608,12508	21,4947943	1,235589917
15	11,57850365	-13,88131249	49,342528	53,6855432	1605,55247	21,2047903	1,144403511
16	8,433813373	-20,13731903	50,82001361	53,0831747	1597,36714	21,3766199	1,151040271
17	8,889282241	-24,78606331	47,94866336	53,4061343	1529,79311	21,1172751	1,172873951
…	…	…	…	…	…	…	…
100	8,605662687	-14,61462659	48,71570011	54,505962	1567,69807	21,2197071	1,169196985

STATEMENT OF ORIGINALITY

This is to certify that to the best of my knowledge; the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Mathieu Feigean

ABSTRACT

This project analysed processes leading to the emergence of collective behaviour patterns. Collective behaviour, considered as self-organized, emerges from individual activities that interplay as the activity unfolds.

One aim of this project was to explore how individuals regulate their activity to participate to the elaboration of collective behaviour. Sport science literature did not consider the individual regulation as a main focus to understand team behaviour. The regulation has been assumed rather than investigated. To this end, we described the variety of informational resources used by team members during a football game. We adopted an epistemological approach that was respectful of how humans regulate their agent-environment coupling, which was the enactive approach. From this approach, sense-making is assumed to be central in delineating the dynamics of the agent-environment coupling, and the phenomenological experience of the agent was seriously considered in the study designs. The results identified various informational resources, which we ranked along a continuum from local resources to global resources.

The subsequent goal was to understand the relationship between individual regulation and its consequences in the collective behaviour. Grounded in the use of a computer simulation tool, the project simulated the spatiotemporal collective behaviour of a multi-agent system built to capture the essentials of football team behaviours and to evaluate how the dynamical outcomes (i.e., the collective behaviour patterns) depend on individual adjustment modalities. These adjustment modalities were implemented in the simulation. More specifically, the simulation study generated a large amount of spatiotemporal data that are hard to capture in ecological situation with natural setting, in order to test to what extent the collective behaviour dynamical outcomes were changed when a single players changed their adjustments. The collective behaviour was characterised through metrics accounting for team spatiotemporal properties such as surface area and team stretching. The results showed a condensed behaviour associated with the local adjustment modality and a deployed behaviour associated with global adjustment modalities.

A complementary study investigated the possibilities of controlling human regulation through interaction rules. The results showed that various interaction rules involved different informational resources and adjustment modality. Moreover, the results demonstrated that a local informational resource did not necessarily involve a local adjustment which describe the complexity of the regulation processes.

Key words. Individual regulation, informational resources, adjustment, enactive approach, simulation.